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Laboratory Evaluation of an In-Situ Coating Process for Mitigation of Lead and Copper in Drinking Water

by
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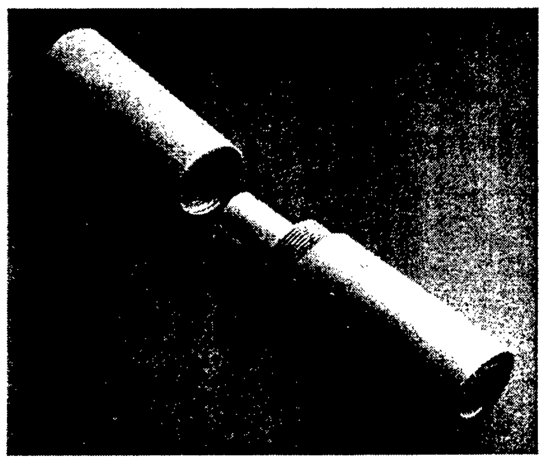

Corrosion of building plumbing can result in reduced service life and adverse health effects such as those associated with high lead blood levels, particularly in children. The U.S. Environmental Protection Agency (USEPA) has established an "Action Level" (AL) of 15 µg/L for lead and 1.3 mg/L for copper in drinking water. Army installations must comply with the increasingly stringent drinking water quality standards enacted at the Federal level and enforced by State regulations.

This study evaluated the effectiveness of in-situ coatings for inhibiting lead corrosion under a variety of water quality parameters in the laboratory. The study compared the in-situ coating system to zinc orthophosphate chemical inhibitor treatment for mitigation corrosion and plumbosolvency. Results indicate that the in-situ epoxy coating provides an effective alternative to conventional chemical treatment for the prevention of lead and copper metal release in a system modeled to simulate a home plumbing system. This study also initiated operation of a Water Treatment Test Facility (WTTF) to determine its viability as a test facility to simulate a variety of water qualities in a home plumbing system. The WTTF operated reliably over the course of the 12-week study and produced valuable information on operating procedures.

Approved for public release; distribution is unlimited.

Foreword

This study was conducted for Headquarters, U.S. Army Corps of Engineers (HQUSACE) under Project 4A162784AT41, "Military Facilities Engineering Technology"; Work Unit FM-C75, "Corrosion Control of Building Plumbing." The technical monitor was Malcolm McLeod, CECPW-ES.

The work was performed by the Materials Science and Technology Division (FL-M) of the Facilities Technology Laboratory (FL), U.S. Army Construction Engineering Research Laboratories (USACERL). The USACERL principal investigator was Vincent F. Hock. The USACERL research assistant was Erik Kirstein. Kent Smothers and Jeremy Overmann are associated with the Illinois State Water Survey and Jane Anderson with the U.S. Center for Public Works (USACPW). Dr. Ilker R. Adiguzel is Acting Chief, CECER-FL-M; Dr. Alan Moore is Chief, CECER-FL, and Donald F. Fournier is Acting Operations Chief, CECER-FL. The USACERL technical editor was William J. Wolfe, Technical Resources.

COL James T. Scott is Commander and Dr. Michael J. O'Connor is Director of USACERL.

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1 Introduction

Army installations must comply with the increasingly stringent drinking water quality standards enacted at the Federal level and enforced by State regulations. The Safe Drinking Water Act (SDWA) of 1974 required the U.S. Environmental Protection Agency (USEPA) to develop a list of maximum contaminant levels (MCLs) for inclusion in the National Primary Drinking Water Regulations (NPDWR).* A September 1986 amendment to the SDWA went on to ban the use of lead in public water system pipes, solder, and flux. On 7 June 1991, the USEPA finalized these regulations with a requirement of an MCL for lead concentration of 0.015 mg/L measured in the ninetieth percentile taken from cold water kitchen faucets following a 6- to 8-hour stagnation time. In September 1992, the USEPA finished Volume II of the Lead and Copper Rule (LCR), which is the guidance manual on corrosion control treatment. While the USEPA did not ultimately set MCLs for lead and copper, it did set "Action Levels" (ALs), which, if exceeded, require that certain actions be taken. These actions must be continued as long as the specified level is exceeded.

Much attention has focused on the costly remediations required when the lead action level is exceeded. This issue plays a significant role in the national debate over unfunded environmental mandates, and more specifically, in the search for cost-effective ways to ensure that drinking water at Army installations meets all standards for quality and compliance with applicable laws. Two possible strategies to ensure that drinking water meets current standards are by chemical treatment and by application of coatings or linings to pipes or tubes to mitigate corrosion or plumbosolvency. This study was undertaken to evaluate the effectiveness of an in-situ epoxy coating in comparison with a proven chemical treatment for potable water.

* "Minimization of Lead Corrosion in Drinking Water," *Materials Performance* (August 1990), pp 45-49.

Objectives

The purposes of this study were to initiate operation of the Water Treatment Test Facility (WTTF), and to execute a 12-week test program. This study evaluated the effectiveness of an in-situ blown epoxy coating for the mitigation of lead and copper corrosion in comparison to both a control and a proven, effective chemical treatment (zinc orthophosphate) for potable water. An additional objective of this study was to write an Operations Manual for the WTTF.

Approach

1. This study employed two water qualities: (a) softened and (b) hard water.
2. Samples were taken weekly following an 8-hour standing time from each of the 12 legs and analyzed for lead, copper, total organic carbon (TOC), orthophosphate, zinc, methyl orange alkalinity (M-alkalinity), hardness, pH, and temperature. The results of those analyses are detailed in Tables A1–A12, located in Appendix A to this report. Source water for the loops was Champaign-Urbana tap water (Northern Illinois Water Corporation).*
3. Source water was monitored weekly for copper, TOC, orthophosphate, and zinc. Table A13 includes all these analyses.
4. The soft and hard water supplied to the legs was monitored for background concentrations in all of the analyses listed above (Tables A14 and A15).
5. Oxygen and temperature levels during operation were recorded by on-line instruments; Table A16 lists the average concentrations.
6. The uncoated copper specimens were removed for corrosion weight loss measurements; Table A17 lists these results.

Mode of Technology Transfer

It is anticipated that the results of this study will be incorporated into a Public Works Technical Bulletin (PWTB), to be published by the Corps of Engineers Installation Support Center (CEISC), Alexandria, VA.

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*Northern Illinois Water Corporation (NIWC), 201 Devonshire Road, Champaign, IL 61820, tel.: (217) 352-7001.

2 Laboratory Evaluation of In-Situ Coatings for Corrosion Control

Laboratory Procedure

The water entering the water treatment test facility can be altered mechanically and chemically to produce a water with the desired concentration of hardness, alkalinity, pH, calcium, etc. Several different water qualities (up to four) can be evaluated during each daily cycle by using a computer to control sequencing of valves, pumps, etc. Provisions have been made for testing up to four different chemical treatments for each of the water qualities.

This study employed only two water qualities. One was softened water (<2.0 mg/L hardness as $CaCO_3$) with an alkalinity of ~200 mg/L and a flowing pH of approximately 7.0, and the second was a hard water (municipal supply, ~80 mg/L as $CaCO_3$) with the same alkalinity and a flowing pH of 7.5. The original intent was to operate the hard water system with a pH of 8.0, but the water was not stable in that pH range. The incoming municipal water has a nominal pH of 8.8 to 9.0, so the pH is first lowered and the alkalinity neutralized by the addition of sulfuric acid. Soft water loops are first passed through a water softener to remove most of the hardness. After the acid addition, solutions of first sodium bicarbonate and then sodium hydroxide are injected to raise the alkalinity and pH to the desired levels. The two flow rates employed were 5 and 3 ft per second (fps).* Water flowed through each of the 12 legs for 2 hours each day. Each of the 12 legs in operation had a 3½-in. copper specimen with ½-in. coating of 50/50 tin-lead solder and 3-in. copper specimens. Since the loops are constructed of PVC pipe, these pipe specimens are the only potential source of lead and copper in the system except the incoming city water (Figure 1).

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*1 ft = 0.305 m; 1 in. = 25.4 m.

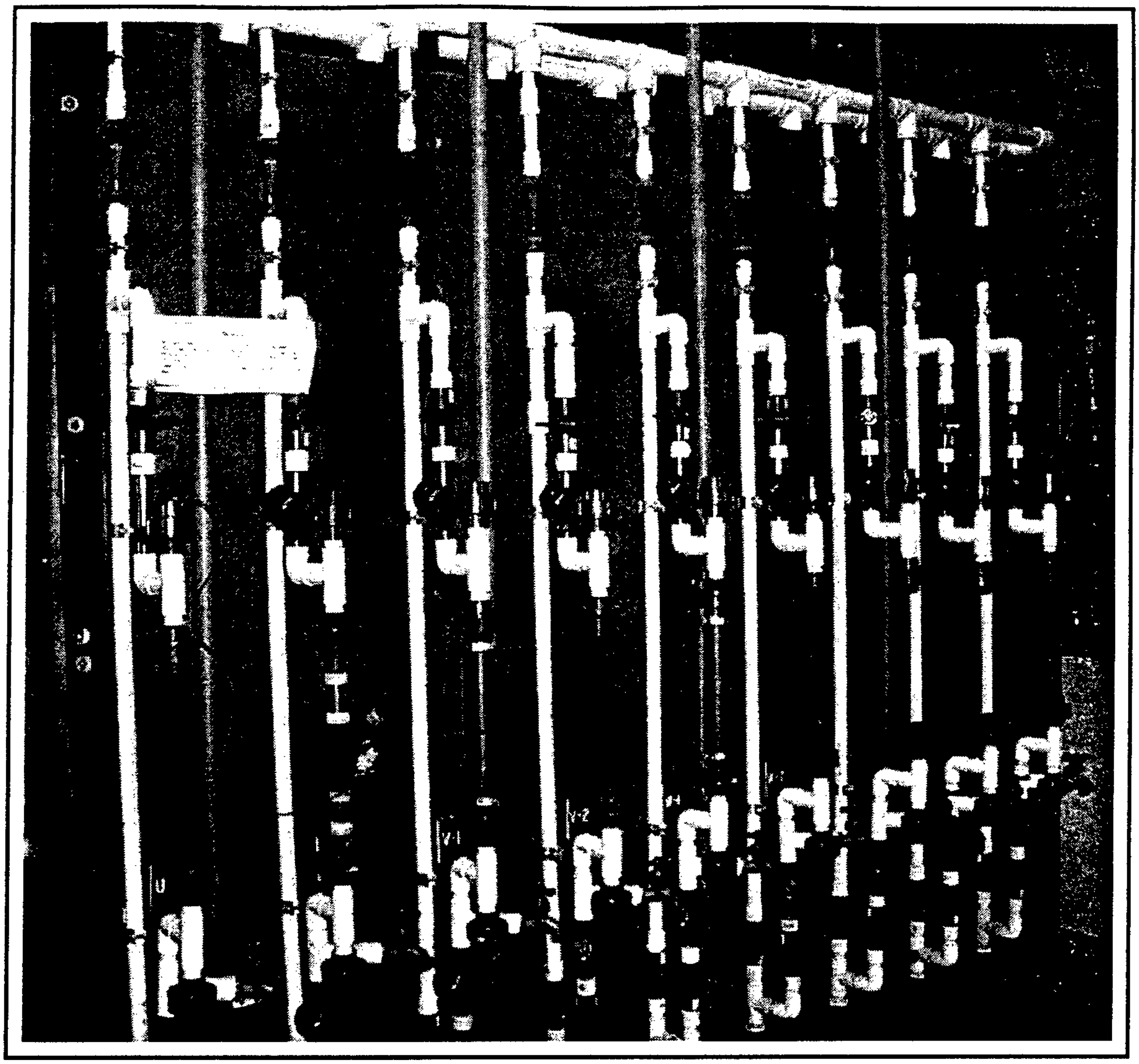

Figure 1. Water treatment test facility showing test specimen holder installed in the test loops.

The operating parameters for this study are included in the *Water Treatment Test Facility Operation Manual*. Pump settings, vat charges, cycle times, etc. are detailed in that document. Please refer to that manual for additional information on the operating conditions employed in this study.

Samples were taken weekly following an 8-hour standing time from each of the 12 legs and analyzed for lead, copper, total organic carbon (TOC), orthophosphate, zinc, methyl orange alkalinity (M-alkalinity), hardness, pH, and temperature. The results of those analyses are detailed in Tables A1–A12. Source water for the loops was Champaign-Urbana tap water (Northern Illinois Water Corporation). This was monitored weekly for copper, TOC, orthophosphate, and zinc. Table A13 includes all these analyses. The soft and hard water supplied to the legs was monitored for background concentrations in all of the analyses listed above. This information is provided in Tables A14 and A15. Oxygen and temperature levels during operation were recorded by on-line instruments and the average concentrations are listed in Table A16. The uncoated copper specimens were removed for corrosion weight loss measurements. These results are presented in Table A17.

Analytical Data

Tables A1, A2, A3, and A4 detail the analytical results for the four legs that used specimens coated with the in-situ epoxy coating. None of these four legs showed lead or copper concentrations significantly above background level. One concern with the use of the in-situ epoxy coating was the possible decomposition of the coating, which might result in the release of organic compounds. The supply water was monitored for background TOC levels (Table A13), and the average value for the 12-week period was 1.8 mg/L. The average for the four legs that used the in-situ epoxy coated specimens was 1.7 to 1.9 mg/L, indicating no significant decomposition of the epoxy coating. Neither the flow rate (5 fps and 3 fps), nor the water quality had any apparent impact on the lead or copper concentrations. The temperature was relatively constant throughout the course of the experiment, with a range of 16.9 to 20.3 °C, and an average value of 17.9 to 18.6 °C in the individual legs. The pH for the standing samples in all of the legs was constant at approximately 7.0 (±0.3).

The data from the samples collected in the four legs treated with zinc orthophosphate are listed in Tables A5, A6, A7, and A8. Lead corrosion was obviously inhibited by the zinc orthophosphate, since very few of the samples contained lead concentrations above the detection limit. Copper concentrations were measurable for all 12 weeks in each of the four legs using zinc orthophosphate. The average concentration of copper was highest (0.51 mg/L) in the soft water, 3 fps leg. The average concentration of copper in the other three legs was very consistent at 0.41, 0.43, and 0.44 mg/L. None of the copper concentrations exceeded the USEPA 1.3 mg/L AL. The average TOC concentration in these four legs was very similar to the coated specimen legs, ranging from 1.7 to 2.0 mg/L. Zinc concentrations averaged between 0.86 and 0.96 mg/L, and the average orthophosphate concentrations were 1.52 to 1.91 mg/L. The zinc orthophosphate treatment provided satisfactory corrosion inhibition of lead and copper.

Corrosion rates for both lead and copper was highest in the control legs (Tables A9, A10, A11, and A12). The soft water, 5 fps leg had the lowest lead levels, averaging 1.04 µg/L. The other three legs were more consistent with each other, averaging 2.10 to 2.74 µg/L. Hard water showed higher corrosion rates than soft water for lead at both flow rates. However, the average copper concentrations were more consistent, ranging from 1.03 to 1.26 mg/L for the four control legs. Copper concentrations exceeded the AL of 1.3 mg/L in 41 percent of the samples from these legs.

Once again, TOC concentrations were comparable to both the in-situ epoxy coated specimen legs and the zinc orthophosphate treated legs, ranging from 1.8 to 2.0 mg/L. Champaign-Urbana tap water was used as the supply for these loops, and was monitored for copper, TOC, orthophosphate, and zinc (Table A13). Zinc and copper concentrations were below instrument detection limits for all of the samples analyzed. The TOC concentrations averaged 1.8 mg/L for the duration of the test run. Trace amounts of orthophosphate recorded in two samples, which may have been due to system pH upsets that resulted in a release of phosphate from existing deposits on the distribution piping.

Flowing samples from the hard and soft water supply loops (Tables A14 and A15) were analyzed during most of the 12-week period for the same constituents as the legs. Oxygen concentrations averaged 3.6 mg/L in the soft water loop and 3.8 mg/L in the hard water loop. The temperatures were, as expected, much lower in the flowing samples, averaging near 10 °C for both loops. The copper, zinc, and lead concentrations were found to be at or below the detection limit. The average temperature and oxygen concentrations for the flowing hard and soft water loops in both the conditioning phase and the 12-week test run are included in Table A16.

Weight Loss Data

Corrosion weight loss measurements were conducted on the 3-in. copper specimens installed in the zinc orthophosphate and control loops (Figure 2). Table A17 contains corrosion rates reported both as MDD (milligrams/decimeter^2/day) and MPY (millimeters penetration/year). The corrosion rate was somewhat higher for the soft water than the hard water for both velocities in the control and treated legs. The 5 fps velocity legs had higher corrosion rates than the comparable 3 fps legs for three of the four water quality/velocity combinations. The soft water legs treated with zinc orthophosphate had the same MPY for both the 3 and 5 fps legs. The effect of velocity on the corrosion rate of copper was obvious in the control legs. The copper MPY for the 5 fps legs in both the hard and soft waters was almost 20 percent higher than in the 3 fps legs. The recommended maximum velocity for copper tube in potable water systems in 4 fps; flow rates higher than that can cause an increase in corrosion rates. The corrosion rates for the four legs using zinc orthophosphate ranged from 0.34 to 0.49 MPY, and the corrosion rates in the control legs were 0.95 to 1.19 MPY.

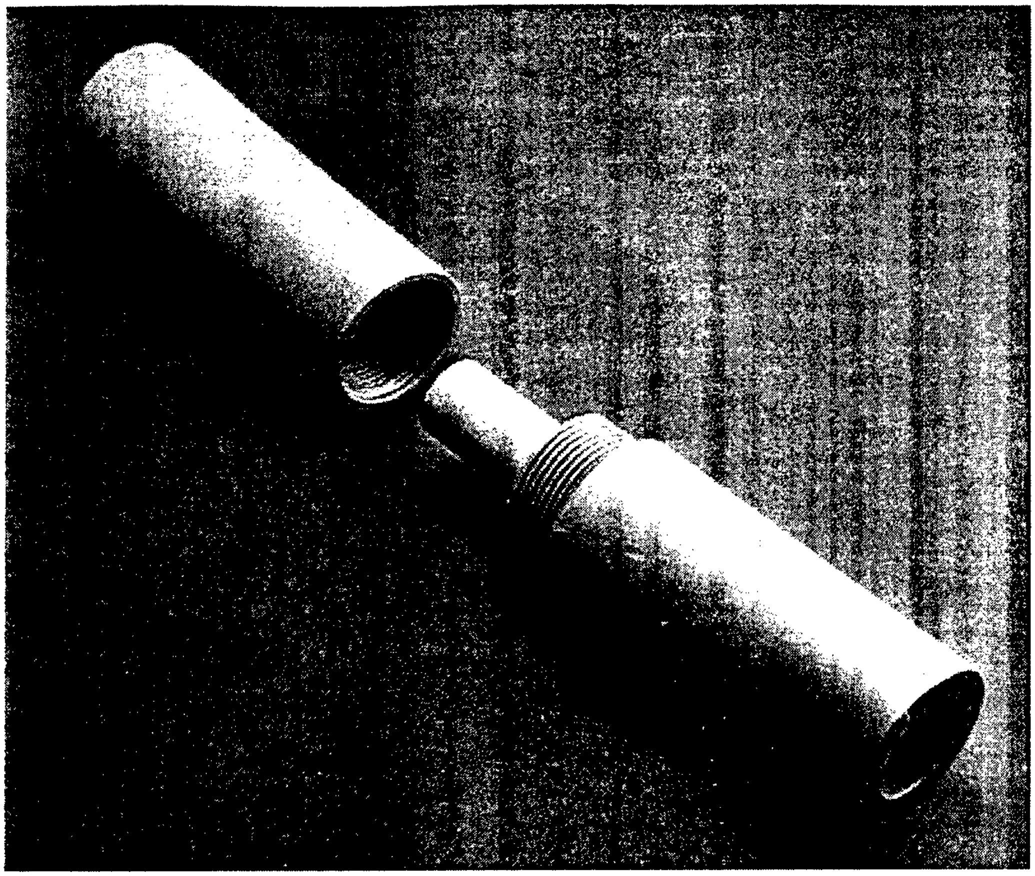

Figure 2. Specimen holder with copper pipe specimen installed.

Copper corrosion rates of 1.0 MPY are much higher than desired for potable water systems. Corrosion weight loss determinations were not performed on the 3½-in. specimens since ½ in. of the inside is coated with 50/50 tin-lead solder, and it would be impossible to determine how much weight loss was attributable to copper and how much was lead or tin.

Wilcoxon Signed Rank Test

The Wilcoxon Signed Rank Test (Wilcoxon) is a nonparametric statistical analysis comparing two related (dependent) samples. The Wilcoxon takes into account the size of the rank order differences within pairs of data, as opposed to the numerical values of the differences. Paired data were examined among three different water treatment conditions (epoxy coating, zinc orthophosphate, and control) under four different water quality conditions. Table 1 summarizes the water treatments and qualities. The Wilcoxon was applied to look for differences among the three different water treatments.

Table 1. Sample identifications.

Sample Identification	Water Quality	Water Treatment	Treatment
A-1		1	Coating
I-1	1	2	Zinc Orthophosphate
R-1		3	Control
D-3		1	Coating
L-2	2	2	Zinc Orthophosphate
S-1		3	Control
F-1		1	Coating
M-1	3	2	Zinc Orthophosphate
V-1		3	Control
G-1		1	Coating
P-2	4	2	Zinc Orthophosphate
W-1		3	Control

In this experiment, copper, lead, and total organic carbon (TOC) values in water were recorded. The Wilcoxon was performed separately for each of these three elements. Appendix A gives statistical data for element concentrations versus water treatments within a water quality group. Statistical data for copper concentrations appear first, then lead and TOC; water quality is shown as WQ, and water treatment as WT. Table 2 lists the Wilcoxon for copper, lead, and TOC.

The numbers corresponding to the water treatments and qualities are as designated in Table 1. The Wilcoxon tables are broken down into three sections:

1. *Counts of Differences*: This section presents the number of times element values from a given WQ and WT (listed along the left-hand column) are greater than the values for one of the other WTs (listed along the top row).
2. *Z*: This section presents the sum of the signed ranks divided by the square root of the sum of the squared ranks. This statistic is given meaning by the probability value obtained in statistical tables.*
3. *Two-Sided Probabilities*: The statistical significance to the corresponding Z-value is given in this section. A probability of 1.000 means the paired rankings are indistinguishable from one another and the differences between them are insignificant. A probability of 0.001 means there is a 99.9 percent probability the paired rankings are distinguishable and significantly different.

*Vincent F. Hock, Henry Cardenas, Kent W. Smothers, and Eric D. Zelsdorf, *Control of Plumbosolvency in Building Plumbing Supplies*, Technical Report (TR) 96/74/ADA315200 (U.S. Army Construction Engineering Research Laboratories [USACERL], July 1996).

Table 2. Summaries of the Wilcoxin for copper, lead, and TOC values.

Water Quality	Copper	Lead	TOC
WQ1	WT1 was the best treatment for this WQ, having a 99.8 percent significance over WT2 and WT3. WT2 ranked second, also having a 99.8 percent significance over WT3.	The results for comparing WT1 and WT2 were not distinguishable. However, both WT1 and WT2 were significantly better than WT3 (over 99 percent).	There was no significant difference between WT1 and WT2, as well as between WT2 and WT3. The results for WT1 and WT3 were 96.5 percent distinguishable, with WT1 prevailing.
WQ2	The results for WQ2 were almost identical to WQ1. WT1 had over a 99 percent significance over WT2 and WT3. WT2 had a 99.7 percent significance over WT3.	The results were similar to the WQ1 results. WT1 and WT2 were not distinguishable, but both WTs prevailed over WT3.	None of the three water treatments were statistically distinguishable from one another for this water quality.
WQ3	The results were exactly identical to the results obtained for WQ1. WT1 was the best, followed by WT2 and WT3.	In this case, WT1 and WT2 were distinguishable, with WT2 having a 95.7 percent significance over WT1. Both WT1 and WT2 were significantly better than WT3 (over 95 percent).	The results for WQ3 were the same as for WQ2. None of the three water treatments were statistically distinguishable from one another.
WQ4	Once again the results were similar to WQ1. Order of performance: WT1, WT2, WT3.	WT1 had a slight significant edge over WT2 (92 percent), and WT3 had the most number of larger lead values, placing it last among the three water treatments.	For WQ4, WT2 was slightly significantly different over WT1 (91.9 percent). The remaining results were not distinguishable.

Table 3 summarizes the results shown in Table 2, and ranks the water treatments for the reduction of each element. The data in Table 3 shows that the epoxy coating was the most effective for reducing copper concentrations in the pipe loop. Both the epoxy coating and the zinc orthophosphate were effective in reducing lead values, and both coatings seemed to work equally well in comparison with the control. However, all three water treatments were statistically indistinguishable from one another in reducing TOC values. None of the water treatments stood out as a good agent for the reduction of TOC in water.

Table 3. Wilcoxon signed rank test results.

Water Quality	Copper Water Treatment Rank			Lead Water Treatment Rank			TOC Water Treatment Rank		
WQ1	WT1	WT2	WT3	WT1, WT2	WT3	—	WT1, WT2, WT3	—	—
WQ2	WT1	WT2	WT3	WT1, WT2	WT3	—	WT1, WT2, WT3	—	—
WQ3	WT1	WT2	WT3	WT2	WT1	WT3	WT1, WT2, WT3	—	—
WQ4	WT1	WT2	WT3	WT1	WT2	WT3	WT1, WT2, WT3	—	—

Visual Observations

Visual observations were made for all of the 3½-in. and 3-in. specimens after completing the test run, and before making any weight loss determinations. The exterior surface of each specimen was discolored, indicating there had been some seepage of water between the specimen and the holder. The specimens designated by “C” are the 3-in. copper specimens and those designated by “P” are the 3½-in. copper and tin-lead solder specimens. In addition to the coated copper test specimens, Figure 3 shows a 4-in. diameter steel pipe that was coated with approximately 14 mils (1 mil = 0.001 in.) of epoxy in situ during a field demonstration at Elmendorf AFB, Anchorage, AL. Table 4 lists the visual observations. (Appendix B contains photographs of the test specimens listed in Table 4.)

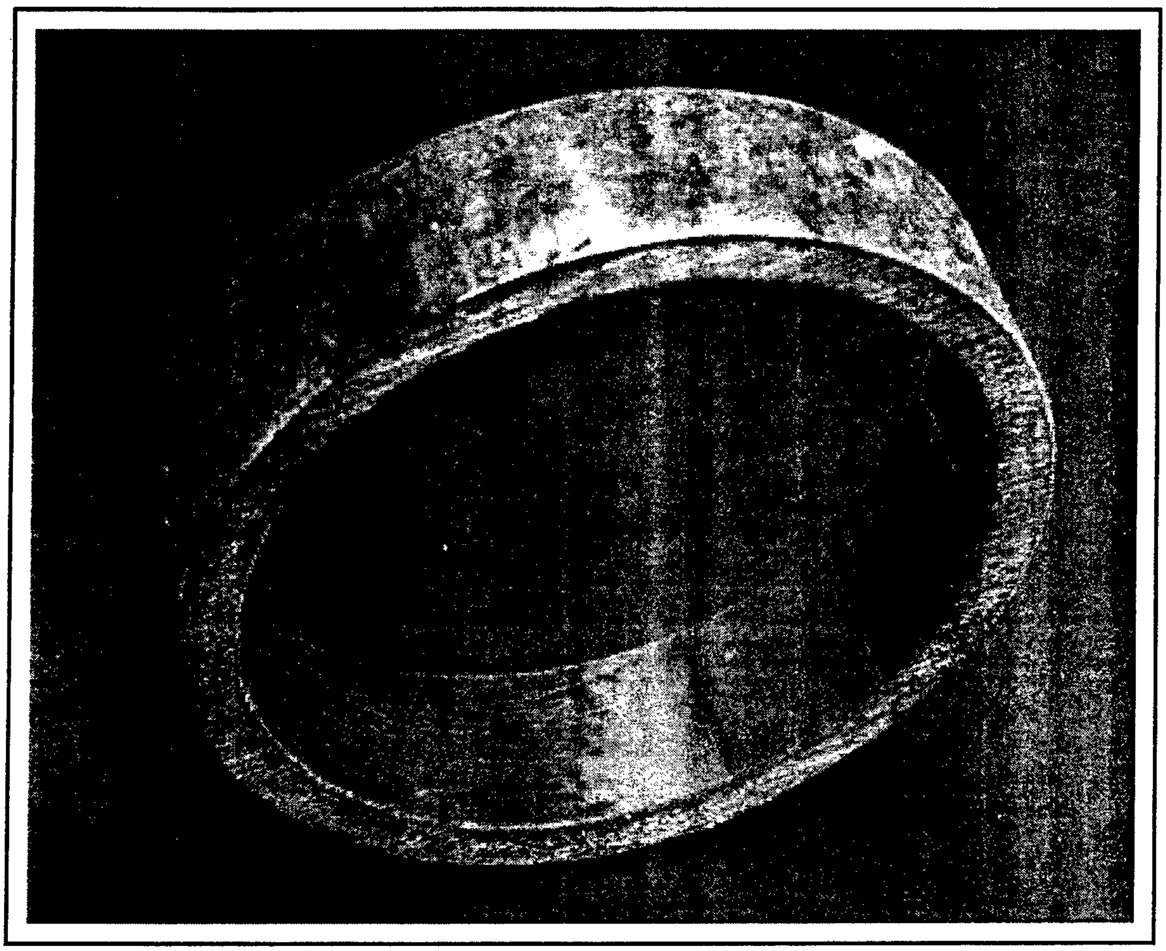

Figure 3. Four-in. steel pipe coated with approximately 14 mils epoxy, in situ.

Table 4. Visual observations on all 3-in. and 3½-in. specimens after the test run.

	In-situ Epoxy coating		Zinc Orthophosphate		Controls	
	Specimen	Observation	Specimen	Observation	Specimen	Observation
Hard water, 5 fps	C11	Very thin, yellow-tan colored deposit on epoxy coating.	C06	Very thin, soft, surface deposit with a harder, blue-green and gray deposit underneath.	C13	Very thin, soft, surface deposit and a harder, yellow-tan deposit beneath, which increases in thickness near the stamped end of the specimen.
	P11	Very thin, soft, surface deposit with a harder orange-tan deposit beneath, and an orange-tan colored stain on epoxy coating.	P06	Very thin, soft, yellow-gray deposit on solder. Very thin, soft, tan-brown deposit on the copper surface.	P13	Very thin, soft, surface deposit with a harder, yellow-tan deposit on the solder and copper surfaces.
Soft water,5 fps	C14	Tan colored stain on epoxy coating.	C09	Very thin, soft, surface deposit with a harder blue-green and yellow-tan deposit underneath.	C01	Very thin, soft, surface deposit with a harder, yellow-tan deposit underneath.
	P14	Very thin, yellow-tan deposit and yellow-tan colored stain on epoxy coating.	P09	Very thin, soft, surface deposit with a harder, gray and yellow-tan deposit on solder. Very thin, soft, surface deposit with a harder, yellow-tan and tan-brown deposits on copper surfaces.	P01	Very thin, soft, surface deposit with a harder, yellow-tan deposit on solder. Very thin, hard, tan deposit on copper.
Hard water, 3 fps	C10	Very thin, yellow-tan colored deposit on epoxy coating.	C07	Very thin, soft, surface deposit with a harder, blue-green and tan deposit beneath.	C02	Very thin, soft, surface deposit with a harder, yellow-tan deposit near the stamped end, dark discoloration of the interior surface near the other end.
	P10	Very thin, yellow-tan deposit and yellow-tan colored stain on epoxy coating.	P07	Very thin, soft, gray deposit on solder. Very thin, tan deposit on copper.	P02	Very thin, soft, surface deposit with a harder, yellow-tan deposit on solder. Very thin, hard, yellow-tan deposit on copper.
Soft water, 3 fps	C12	Light yellow-tan colored stain on epoxy coating.	C08	Very thin, soft, surface deposit with a harder, blue-green and yellow-tan deposit underneath.	C03	Very thin, soft, surface deposit with a harder, tan deposit beneath.
	P12	Very thin, light tan deposit and light tan-colored stain on epoxy coating.	P08	Very thin, soft, surface deposit with a harder, gray deposit on solder. Very thin, soft, surface deposit with a harder, tan-brown deposit beneath on the copper.	P03	Very thin, soft, surface deposit with a harder, yellow-tan and gray deposit on solder. Very thin, hard, yellow-tan deposit on copper.

3 Conclusions and Recommendations

The results of this study clearly indicate that the in-situ epoxy coating provides an effective alternative to conventional chemical treatment for the prevention of lead and copper metal release in a system modeled to simulate a home plumbing system. Lead concentrations were lower than the USEPA AL for all of the samples, but this was probably due to the very small surface area of lead available. The control samples had measurable lead concentrations in most samples (>80 percent), with three of the legs averaging more than 2 µg/L lead for the standing samples. The zinc orthophosphate and in-situ epoxy coating legs all had only occasional (<20 percent) lead concentrations above the detection limits. Copper concentrations were very high in the control legs, having average copper concentrations near the USEPA AL of 1.3 mg/L (1.03–1.26 mg/L) for each leg, with ~41 percent of the samples exceeding the AL. The zinc orthophosphate exhibited a significant improvement in the copper concentrations found in the standing samples for all water qualities, with none of the samples exceeding the AL. The average copper concentrations varied from 0.41 to 0.51 mg/L. The in-situ epoxy-coated legs showed an even more dramatic reduction of copper levels than the zinc orthophosphate treatment, with only one of the 48 samples having a copper concentration (0.030 mg/L) above the detection limit of 0.006 mg/L.

This study also initiated operation of the WTTF, and determined its viability as a test facility to simulate a variety of water qualities in a home plumbing system. The WTTF operated reliably over the course of the 12-week study, which gathered valuable information on operating procedures. Comprehensive information on the operation of the loop, computer programs, and equipment specifications can be found in the *Water Treatment Test Facility Operation Manual.*

It is recommended that draft guidance be developed for the use of nonchemical treatment such as "In-Situ Pipe Coatings for Mitigation of Corrosion and Plumbosolvency." The draft guidance should be incorporated into a draft Center for Public Works Technical Bulletin (PWTB) and Corps of Engineers Guide Specifications (CEGS) 15400 and 15401.

Appendix A: Tables

Table A1. Sample A-1, "hard" water, 5 fps, coating.

Date Sampled	WK 1	WK 2	WK 3	WK 4	WK 5	WK 6	WK 7	WK 8	WK 9	WK 10	WK 11	WK 12
	12/21/95	12/28/95	1/4/96	1/11/96	1/18/96	1/25/96	2/1/96	2/8/96	2/15/96	2/22/96	2/29/96	3/7/96
Lead (g/L)	<1.04	<1.04	<1.04	<1.04	<1.04	<0.54	<0.54	<1.04	<1.04	<1.04	<1.04	<1.04
Copper (mg/L)	<0.006	<0.006	<0.006	<0.006	<0.006	<0.006	<0.006	<0.006	<0.006	<0.006	<0.006	<0.006
Total Organic Carbon (mg/L)	2.2	2.4	2.0	1.4	1.7	1.4	1.5	1.7	1.7	1.5	1.9	1.8
Orthophosphate (mg/L as PO_4)	<0.1	<0.0	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Zinc (mg/L)	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
M-Alkalinity (mg/L as $CaCO_3$)	180	174	162	172	216	188	190	208	192	210	176	184
Hardness (mg/L as $CaCO_3$)	89	82	92	72	88	71	87	71	62	83	67	80
pH	6.9	6.7	6.8	6.7	7.1	6.9	6.8	7.2	6.9	6.7	6.7	7.0
Temperature (°C)	18.3 (est.)	18.3 (est.)	18.3 (est.)	19.4	17.5	19.1	18.3	17.2	18.5	18.3 (est.)	18.0	16.9

Table A2. Sample D-3, "soft" water, 5 fps, coating.

Date Sampled	WK 1	WK 2	WK 3	WK 4	WK 5	WK 6	WK 7	WK 8	WK 9	WK 10	WK 11	WK 12
	12/21/95	12/28/95	1/4/96	1/11/96	1/18/96	1/25/96	2/1/96	2/8/96	2/15/96	2/22/96	2/29/96	3/7/96
Lead (g/L)	<1.04	<1.04	<1.04	<1.04	<1.04	<0.54	<0.54	<1.04	<1.04	<1.04	<1.04	<1.04
Copper (mg/L)	<0.006	<0.006	<0.006	<0.006	<0.006	<0.006	<0.006	<0.006	<0.006	<0.006	<0.006	<0.006
Total Organic Carbon (mg/L)	2.9	1.4	2.1	1.6	1.6	1.6	1.3	1.8	1.7	1.5	1.7	1.7
Orthophosphate (mg/L as PO_4)	<0.1	<0.1	0.43	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Zinc (mg/L)	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
M-Alkalinity (mg/L as $CaCO_3$)	194	188	262*	184	282*	178	172	224	172	208	192	204
Hardness (mg/L as $CaCO_3$)	0.8	0.9	0.9	0.6	0.7	0.5	0.6	1.1	0.8	0.9	0.7	0.9
pH	6.9	6.7	9.0*	6.8	9.2*	6.8	7.0	7.0	6.8	7.0	6.8	6.9
Temperature (°C)	17.9 (est.)	17.9 (est.)	17.6	19.2	17.3	17.5	17.6	17.2	18.7	17.6	18.5	17.2

* Acid pump was air-locked.

Table A3. Sample F-1, "hard" water, 3 fps, coating.

Date Sampled	WK 1	WK 2	WK 3	WK 4	WK 5	WK 6	WK 7	WK 8	WK 9	WK 10	WK 11	WK 12
	12/21/95	12/28/95	1/4/96	1/11/96	1/18/96	1/25/96	2/1/96	2/8/96	2/15/96	2/22/96	2/29/96	3/7/96
Lead (g/L)	<1.04	<1.04	<1.04	<1.04	<1.04	4.88	3.87	1.40	<1.04	1.74	<1.04	2.06
Copper (mg/L)	<0.006	<0.006	<0.006	<0.006	<0.006	<0.006	<0.006	<0.006	<0.006	<0.006	<0.006	<0.006
Total Organic Carbon (mg/L)	2.2	2.6	2.0	2.0	1.6	1.7	1.6	1.8	1.9	1.7	1.6	1.8
Orthophosphate (mg/L as PO_4)	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Zinc (mg/L)	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
M-Alkalinity (mg/L as $CaCO_3$)	176	194	164	172	200	198	186	222	178	200	180	188
Hardness (mg/L as $CaCO_3$)	91	95	94	74	79	70	85	86	56	88	61	84
pH	7.2	6.7	6.9	6.8	7.1	6.9	6.8	7.0	6.9	7.1	6.9	6.9
Temperature (°C)	18.6 (est.)	18.6 (est.)	17.8	20.3	17.9	18.2	19.0	17.8	19.4	17.9	19.1	18.1

Table A4. Sample G-1, "soft" water, 3 fps, coating.

Date Sampled	WK 1	WK 2	WK 3	WK 4	WK 5	WK 6	WK 7	WK 8	WK 9	WK 10	WK 11	WK 12
	12/21/95	12/28/95	1/4/96	1/11/96	1/18/96	1/25/96	2/1/96	2/8/96	2/15/96	2/22/96	2/29/96	3/7/96
Lead (g/L)	<1.04	<1.04	<1.04	<1.04	<1.04	<0.54	<0.54	<1.04	1.07	<1.04	<1.04	<1.04
Copper (mg/L)	<0.006	0.0304	<0.006	<0.006	<0.006	<0.006	<0.006	<0.006	<0.006	<0.006	<0.006	<0.006
Total Organic Carbon (mg/L)	2.3	2.3	1.9	1.9	2.4	1.6	1.5	1.7	2.0	1.6	1.8	2.0
Orthophosphate (mg/L as PO4)	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Zinc (mg/L)	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
M-Alkalinity (mg/L as CaCO3)	192	172	148	196	306*	198	186	206	194	204	192	198
Hardness (mg/L as CaCO3)	0.9	1.2	0.9	0.6	0.6	0.5	0.6	1.1	0.8	2.3	0.8	0.9
pH	6.9	6.7	6.8	6.9	9.0*	6.8	6.9	7.0	6.9	7.2	6.8	6.8
Temperature (°C)	18.6 (est.)	18.6 (est.)	18.5	20.2	17.9	18.3	18.9	17.8	19.4	17.2	19.0	18.0

* Acid pump was air-locked.

Table A5. Sample I-1, "hard" water, 5 fps, zinc orthophosphate.

Date Sampled	WK 1	WK 2	WK 3	WK 4	WK 5	WK 6	WK 7	WK 8	WK 9	WK 10	WK 11	WK 12
	12/21/95	12/28/95	1/4/96	1/11/96	1/18/96	1/25/96	2/1/96	2/8/96	2/15/96	2/22/96	2/29/96	3/7/96
Lead (g/L)	<1.04	<1.04	<1.04	<1.04	<1.04	<0.54	<0.54	<1.04	<1.04	1.52	<1.04	<1.04
Copper (mg/L)	0.6740	0.5322	0.5546	0.5515	0.4406	0.3718	0.4368	0.3554	0.3196	0.1988	0.4158	0.3689
Total Organic Carbon (mg/L)	2.3	1.8	1.9	1.9	4.2	2.1	1.5	1.6	2.0	1.4	1.7	1.6
Orthophosphate (mg/L as PO_4)	1.47	2.75	1.64	1.46	1.75	1.01	1.09	1.23	1.17	1.55	1.49	1.67
Zinc (mg/L)	0.8776	0.9815	0.8085	0.9332	1.052	0.7575	0.7325	1.291	0.8467	1.032	0.8861	1.266
M-Alkalinity (mg/L as $CaCO_3$)	176	168	158	172	210	186	188	204	190	222	178	188
Hardness (mg/L as $CaCO_3$)	87	78	91	72	85	56	64	68	49	74	56	72
pH	7.0	6.8	6.9	6.8	7.0	6.8	6.8	7.1	6.8	6.7	6.7	6.8
Temperature (°C)	19.1 (est.)	19.1 (est.)	18.7	20.5	17.8	20.0	19.6	17.8	19.1	19.1 (est.)	19.2	18.6

Table A6. Sample L-2, "soft" water, 5 fps, zinc orthophosphate.

Date Sampled	WK 1	WK 2	WK 3	WK 4	WK 5	WK 6	WK 7	WK 8	WK 9	WK 10	WK 11	WK 12
	12/21/95	12/28/95	1/4/96	1/11/96	1/18/96	1/25/96	2/1/96	2/8/96	2/15/96	2/22/96	2/29/96	3/7/96
Lead (g/L)	<1.04	<1.04	<1.04	<1.04	<1.04	2.04	1.43	<1.04	<1.04	<1.04	<1.04	<1.04
Copper (mg/L)	0.5960	0.1631	0.0563	0.6938	0.0128	0.5345	0.5370	0.4426	0.4919	0.4312	0.4934	0.4468
Total Organic Carbon (mg/L)	2.5	2.3	2.0	1.5	1.6	1.7	1.5	1.8	1.6	1.4	1.7	1.6
Orthophosphate (mg/L as PO_4)	1.64	2.10	2.14	1.24	2.01	1.21	1.38	2.06	1.43	1.81	1.82	1.69
Zinc (mg/L)	0.9468	1.094	0.4859	0.7852	0.5191	0.7594	0.8640	0.9176	0.9313	0.9824	1.067	0.9518
M-Alkalinity (mg/L as $CaCO_3$)	192	190	260*	184	274*	176	176	220	172	204	186	204
Hardness (mg/L as $CaCO_3$)	0.8	0.9	0.8	0.6	0.7	0.4	0.6	1.1	0.8	0.8	0.7	0.9
pH	6.9	6.6	8.9*	6.6	9.1*	6.7	7.0	6.9	6.7	6.8	6.7	6.8
Temperature (°C)	18.6 (est.)	18.6 (est.)	18.5	20.0	17.7	18.1	18.6	17.6	19.4	18.0	19.3	18.0

* Acid pump was air-locked.

Table A7. Sample M-1, "hard" water, 3 fps, zinc orthophosphate.

Date Sampled	WK 1	WK 2	WK 3	WK 4	WK 5	WK 6	WK 7	WK 8	WK 9	WK 10	WK 11	WK 12
	12/21/95	12/28/95	1/4/96	1/11/96	1/18/96	1/25/96	2/1/96	2/8/96	2/15/96	2/22/96	2/29/96	3/7/96
Lead (g/L)	<1.04	<1.04	<1.04	<1.04	<1.04	1.84	1.68	<1.04	<1.04	<1.04	<1.04	<1.04
Copper (mg/L)	0.5664	0.7334	0.4959	0.5117	0.3769	0.4416	0.4627	0.3522	0.3709	0.0862	0.4218	0.3552
Total Organic Carbon (mg/L)	2.4	1.7	2.4	1.7	1.8	1.6	1.6	1.7	3.7	1.6	1.8	1.7
Orthophosphate (mg/L as PO_4)	2.13	1.60	2.13	1.61	5.64*	1.67	2.11	1.78	1.78	1.37	1.59	1.48
Zinc (mg/L)	1.252	0.9731	0.9438	0.9686	3.286*	0.8958	0.9088	0.9625	0.9625	0.7952	0.8188	0.7946
M-Alkalinity (mg/L as $CaCO_3$)	178	182	162	174	214	184	198	212	214	206	180	196
Hardness (mg/L as $CaCO_3$)	93	82	91	75	87	68	86	72	58	83	69	81
pH	7.1	6.7	6.9	6.9	7.0	6.9	6.9	7.1	6.8	6.6	6.7	6.9
Temperature (°C)	19.2 (est.)	19.2 (est.)	18.9	20.7	17.8	20.1	19.7	17.8	19.6	19.2 (est.)	19.2	18.6

* Chemical overfeed

Table A8. Sample P-2, "soft" water, 3 fps, zinc orthophosphate.

Date Sampled	WK 1	WK 2	WK 3	WK 4	WK 5	WK 6	WK 7	WK 8	WK 9	WK 10	WK 11	WK 12
	12/21/95	12/28/95	1/4/96	1/11/96	1/18/96	1/25/96	2/1/96	2/8/96	2/15/96	2/22/96	2/29/96	3/7/96
Lead (g/L)	1.56	<1.04	<1.04	1.65	<1.04	2.38	2.28	<1.04	<1.04	<1.04	<1.04	<1.04
Copper (mg/L)	0.8599	0.4001	0.1162	0.7954	0.0213	0.6888	0.6480	0.5627	0.5757	0.4666	0.5443	0.3837
Total Organic Carbon (mg/L)	2.5	1.8	1.9	1.9	1.5	1.5	1.7	1.5	1.5	1.4	1.9	1.6
Orthophosphate (mg/L as PO_4)	2.21	1.85	2.48	1.74	2.66	1.67	1.70	1.76	1.43	1.56	1.91	1.96
Zinc (mg/L)	1.145	1.093	0.6229	0.9487	0.7327	0.8913	0.8918	0.9665	0.8807	0.8366	1.021	1.053
M-Alkalinity (mg/L as $CaCO_3$)	192	192	264	184	290	180	184	224	180	206	190	214
Hardness (mg/L as $CaCO_3$)	0.9	0.9	0.9	0.6	0.6	0.5	0.6	1.1	0.8	0.9	0.8	0.9
pH	6.9	6.5	8.9*	6.6	9.0*	6.7	7.0	6.9	6.7	6.9	6.7	6.8
Temperature (°C)	19.0 (est.)	19.0 (est.)	18.9	20.5	18.0	18.5	19.2	18.0	19.8	18.3	19.6	18.2

* Acid pump was air-locked.

Table A9. Sample R-1, "hard" water, 5 fps, control.

Date Sampled	WK 1	WK 2	WK 3	WK 4	WK 5	WK 6	WK 7	WK 8	WK 9	WK 10	WK 11	WK 12
	12/21/95	12/28/95	1/4/96	1/11/96	1/18/96	1/25/96	2/1/96	2/8/96	2/15/96	2/22/96	2/29/96	3/7/96
Lead (g/L)	3.59	3.08	1.67	5.06	2.04	4.37	1.40	1.46	1.10	1.45	<1.04	<1.04
Copper (mg/L)	1.270	1.360	1.191	1.186	0.9907	1.346	1.378	0.9035	0.8742	0.7117	1.095	1.267
Total Organic Carbon (mg/L)	3.4	3.0	2.1	1.6	2.6	1.4	1.5	1.6	1.7	1.5	2.0	1.9
Orthophosphate (mg/L as PO_4)	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Zinc (mg/L)	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
M-Alkalinity (mg/L as $CaCO_3$)	174	190	158	174	202	188	188	222	182	200	170	194
Hardness (mg/L as $CaCO_3$)	68	61	61	47	50	32	41	72	46	70	51	75
pH	7.0	6.7	6.9	6.8	7.0	7.0	6.8	7.0	6.8	6.9	6.7	7.0
Temperature (°C)	19.2 (est.)	19.2 (est.)	19.1	21.1	18.2	19.0	19.6	18.2	19.8	18.2	19.7	18.6

Table A10. Sample S-1, "soft" water, 5 fps, control.

Date Sampled	WK 1	WK 2	WK 3	WK 4	WK 5	WK 6	WK 7	WK 8	WK 9	WK 10	WK 11	WK 12
	12/21/95	12/28/95	1/4/96	1/11/96	1/18/96	1/25/96	2/1/96	2/8/96	2/15/96	2/22/96	2/29/96	3/7/96
Lead (g/L)	2.68	<1.04	1.85	2.41	1.47	2.84	<1.04	<1.04	1.22	<1.04	<1.04	<1.04
Copper (mg/L)	1.331	0.4974	1.130	1.036	0.1113	1.366	1.377	0.8237	0.9996	—	1.275	1.355
Total Organic Carbon (mg/L)	2.3	2.2	1.9	1.7	1.9	1.4	1.3	1.9	1.4	1.6	1.7	1.7
Orthophosphate (mg/L as PO_4)	<0.1	<0.1	<0.1	<0.1	0.36	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Zinc (mg/L)	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	—	<0.02	<0.02
M-Alkalinity (mg/L as $CaCO_3$)	190	190	150	204	321	184	178	200	212	—	186	188
Hardness (mg/L as $CaCO_3$)	0.8	51	0.8	0.5	0.6	0.5	0.8	1.2	0.8	—	1.0	0.9
pH	6.9	6.8	6.9	6.8	9.1*	6.7	6.9	6.9	6.8	7.3	6.7	6.8
Temperature (°C)	19.0 (est.)	19.0 (est.)	19.0	20.7	18.1	18.8	19.5	18.1	19.8	17.3	19.7	18.2

* Acid pump was air-locked.

Table A11. Sample V-1, "hard" water, 3 fps, control.

Date Sampled	WK 1	WK 2	WK 3	WK 4	WK 5	WK 6	WK 7	WK 8	WK 9	WK 10	WK 11	WK 12
	12/21/95	12/28/95	1/4/96	1/11/96	1/18/96	1/25/96	2/1/96	2/8/96	2/15/96	2/22/96	2/29/96	3/7/96
Lead (g/L)	3.01	2.59	2.56	6.04	2.22	3.62	2.03	3.18	2.65	1.50	2.00	1.47
Copper (mg/L)	1.329	1.400	1.278	1.282	0.8826	1.223	1.498	1.022	1.221	0.8513	1.368	1.422
Total Organic Carbon (mg/L)	2.8	2.1	2.0	1.6	2.1	1.4	1.6	1.9	1.7	1.6	1.7	1.8
Orthophosphate (mg/L as PO_4)	<0.1	<0.1	<0.1	<0.1	0.26	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Zinc (mg/L)	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
M-Alkalinity (mg/L as $CaCO_3$)	184	200	162	166	200	198	176	218	178	200	168	194
Hardness (mg/L as $CaCO_3$)	77	95	91	66	70	54	73	83	54	76	58	83
pH	7.1	6.8	6.9	6.8	7.1	6.9	6.8	7.0	6.8	6.9	6.7	7.0
Temperature (°C)	18.2 (est.)	18.2 (est.)	19.4	21.6	19.0	19.3	19.9	18.6	20.2	18.6	20.3	19.0

Table A12. Sample W-1, "soft" water, 3 fps, control.

Date Sampled	WK 1	WK 2	WK 3	WK 4	WK 5	WK 6	WK 7	WK 8	WK 9	WK 10	WK 11	WK 12
	12/21/95	12/28/95	1/4/96	1/11/96	1/18/96	1/25/96	2/1/96	2/8/96	2/15/96	2/22/96	2/29/96	3/7/96
Lead (g/L)	4.13	2.63	3.18	4.96	<0.54	3.18	1.12	1.83	2.53	1.08	2.06	<1.04
Copper (mg/L)	1.431	1.015	1.567	1.380	0.1076	1.592	1.580	1.148	1.293	—	1.477	1.316
Total Organic Carbon (mg/L)	2.5	2.4	2.0	1.8	2.1	1.4	1.7	1.8	1.6	—	1.8	1.6
Orthophosphate (mg/L as PO_4)	<0.1	<0.1	<0.1	<0.1	0.26	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Zinc (mg/L)	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	—	<0.02	<0.02
M-Alkalinity (mg/L as $CaCO_3$)	192	182	152	190	314	186	188	212	186	—	198	214
Hardness (mg/L as $CaCO_3$)	1.1	0.9	0.8	1.2	0.6	0.9	0.8	1.3	1.0	—	1.2	1.0
pH	6.9	6.6	6.8	6.7	9.1*	6.7	6.9	6.9	6.8	—	6.8	6.8
Temperature (°C)	19.6 (est.)	19.6 (est.)	19.2	21.2	18.7	19.2	19.8	18.5	20.2	19.6 (est.)	20.1	18.7

* Acid pump was air-locked.

Table A13. Champaign-Urbana tap water (source water for pipe loop).

Date Sampled	WK 1	WK 2	WK 3	WK 4	WK 5	WK 6	WK 7	WK 8	WK 9	WK 10	WK 11	WK 12
	12/21/95	12/28/95	1/4/96	1/11/96	1/18/96	1/25/96	2/1/96	2/8/96	2/15/96	2/22/96	2/29/96	3/7/96
Copper (mg/L)	<0.006	<0.006	<0.006	<0.006	<0.006	<0.006	<0.006	<0.006	-	—	—	—
Total Organic Carbon (mg/L)	3.9	2.6	1.8	1.2	1.6	1.2	1.4	1.5	1.9	1.4	2.0	1.5
Orthophosphate (mg/L as PO_4)	<0.1	<0.1	<0.1	<0.1	0.23	0.13	<0.1	<0.1	—	—	—	—
Zinc (mg/L)	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	—	—	—	—

Table A14. "Soft" water, flowing.

Date Sampled	WK 1	WK 2	WK 3	WK 4	WK 5	WK 6	WK 7	WK 8	WK 9	WK 10	WK 11	WK 12
	12/21/95	12/28/95	1/4/96	1/11/96	1/18/96	1/25/96	2/1/96	2/8/96	2/15/96	2/22/96	2/29/96	3/7/96
Lead (g/L)	—	—	—	—	<1.04	<0.54	<1.04	<1.04	<1.04	<1.04	<1.04	<1.04
Copper (mg/L)	—	—	—	—	<0.006	<0.006	<0.006	<0.006	<0.006	<0.006	<0.006	<0.006
Total Organic Carbon (mg/L)	—	—	—	—	—	1.4	—	—	—	—	—	—
Orthophosphate (mg/L as PO_4)	—	—	—	—	0.26	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Zinc (mg/L)	—	—	—	—	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
M-Alkalinity (mg/L as $CaCO_3$)	—	—	153	180	200	190	180	244	214	—	192	210
Hardness (mg/L as $CaCO_3$)	—	—	1	1	0.6	0.4	0.6	1.2	0.8	1.0	0.7	0.8
pH (nominal)	7	7	7.5	7	7/9*	7	7	7	7	7	7	7
Oxygen (ppm, weekly ave.)	3.1	3.5	3.5	3.7	3.1	3.7	4.2	3.7	4.0	3.4	3.4	4.3
Temperature (°C) (weekly ave.)	11.3	10.8	10.3	10.2	10.0	9.8	9.3	9.6	9.4	9.6	10.2	9.7

* Acid pump was air-locked.

Table A15. "Hard" water, flowing.

Date Sampled	WK 1	WK 2	WK 3	WK 4	WK 5	WK 6	WK 7	WK 8	WK 9	WK 10	WK 11	WK 12
	12/21/95	12/28/95	1/4/96	1/11/96	1/18/96	1/25/96	2/1/96	2/8/96	2/15/96	2/22/96	2/29/96	3/7/96
Lead (g/L)	—	—	—	—	—	1.21	<1.04	<1.04	<1.04	1.25	<1.04	<1.04
Copper (mg/L)	—	—	—	—	—	<0.006	<0.006	<0.006	<0.006	<0.006	<0.006	<0.006
Total Organic Carbon (mg/L)	—	—	—	—	—	—	—	1.5	—	—	—	—
Orthophosphate (mg/L as PO_4)	—	—	—	—	—	0.33	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Zinc (mg/L)	—	—	—	—	—	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
M-Alkalinity (mg/L as $CaCO_3$)	—	—	—	—	—	200	176	211	186	—	180	184
Hardness (mg/L as $CaCO_3$)	—	—	—	—	—	67	80	86	59	86	63	82
pH (nominal)	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5
Oxygen (ppm, weekly ave.)	3.5	3.6	3.7	3.9	3.1	4.3	4.7	4.2	4.0	3.4	3.1	4.1
Temperature (°C) (weekly ave.)	11.0	10.6	9.7	9.9	9.6	9.7	9.1	9.2	8.8	9.0	10.1	9.5

Table A16. Oxygen and temperature averages, flowing.

Water Quality	Parameter	2-WK Conditioning Phase Average	12-WK Experiment Average
"Hard"	Oxygen (ppm)	3.6	3.8
	Temp.(°C)	12.0	9.8
"Soft"	Oxygen (ppm)	3.6	3.6
	Temp.(°C)	12.0	10.1

Table A17. Copper corrosion rates.

	3-inch Copper Insert			
Sample Leg	**Experimental Conditions**	**Weight Loss***	**Corrosion Rate, MDD**	**Corrosion Rate, MPY**
I-1	"hard" water, 5 fps, zinc orthophosphate	0.0805	2.56	0.41
L-2	"soft" water, 5 fps, zinc orthophosphate	0.0959	3.05	0.49
M-1	"hard" water, 3 fps, zinc orthophosphate	0.0665	2.11	0.34
P-2	"soft" water, 3 fps, zinc orthophosphate	0.0959	3.05	0.49
R-1	"hard" water, 5 fps, control	0.217	6.90	1.11
S-1	"soft" water, 5 fps, control	0.233	7.41	1.19
V-1	"hard" water, 3 fps, control	0.187	5.94	0.95
W-1	"soft" water, 3 fps, control	0.1958	6.22	1.00

* Weight loss = W_i - (W_f + cleaning blank of 0.0015 g)

Counts of Differences (Row Variable Greater Than Column)

	WQ2WT1	WQ2WT2	WQ2WT3
WQ2WT1	0	0	0
WQ2WT2	2	0	1
WQ2WT3	6	6	0

Z = (Sum of Signed Ranks)/Square Root (Sum of Squared Ranks)

	WQ2WT1	WQ2WT2	WQ2WT3
WQ2WT1	0		
WQ2WT2	1.342	0	
WQ2WT3	2.201	1.859	0

Two-Sided Probabilities Using Normal Approximation

	WQ2WT1	WQ2WT2	WQ2WT3
WQ2WT1	1.000		
WQ2WT2	0.180	1.000	
WQ2WT3	0.028	0.063	1.000

2 Water Quality 2, Water Treatment 2 lead values were greater than Water Quality 2, Water Treatment 1 values,

0 Water Quality 2, Water Treatment 1 lead values were greater than Water Quality 2, Water Treatment 2 values,

6 Water Quality 2, Water Treatment 3 lead values were greater than Water Quality 2, Water Treatment 1 values,

0 Water Quality 2, Water Treatment 1 lead values were greater than Water Quality 2, Water Treatment 3 values,

6 Water Quality 2, Water Treatment 3 lead values were greater than Water Quality 2, Water Treatment 2 values,

1 Water Quality 2, Water Treatment 2 lead values were greater than Water Quality 2, Water Treatment 3 values.

Counts of Differences (Row Variable Greater Than Column)

	WQ3WT1	WQ3WT2	WQ3WT3
WQ3WT1	0	5	4
WQ3WT2	0	0	0
WQ3WT3	8	12	0

Z = (Sum of Signed Ranks)/Square Root (Sum of Squared Ranks)

	WQ3WT1	WQ3WT2	WQ3WT3
WQ3WT1	0		
WQ3WT2	-2.023	0	
WQ3WT3	2.040	3.059	0

Two-Sided Probabilities Using Normal Approximation

	WQ3WT1	WQ3WT2	WQ3WT3
WQ3WT1	1.000		
WQ3WT2	0.043	1.000	
WQ3WT3	0.041	0.002	1.000

0 Water Quality 3, Water Treatment 2 lead values were greater than Water Quality 3, Water Treatment 1 values,

5 Water Quality 3, Water Treatment 1 lead values were greater than Water Quality 3, Water Treatment 2 values,

8 Water Quality 3, Water Treatment 3 lead values were greater than Water Quality 3, Water Treatment 1 values,

4 Water Quality 3, Water Treatment 1 lead values were greater than Water Quality 3, Water Treatment 3 values,

12 Water Quality 3, Water Treatment 3 lead values were greater than Water Quality 3, Water Treatment 2 values,

0 Water Quality 3, Water Treatment 2 lead values were greater than Water Quality 3, Water Treatment 3 values.

Counts of Differences (Row Variable Greater Than Column)

	WQ4WT1	WQ4WT2	WQ4WT3
WQ4WT1	0	1	0
WQ4WT2	4	0	1
WQ4WT3	10	9	0

Z = (Sum of Signed Ranks)/Square Root (Sum of Squared Ranks)

	WQ4WT1	WQ4WT2	WQ4WT3
WQ4WT1	0		
WQ4WT2	1.753	0	
WQ4WT3	2.805	2.497	0

Two-Sided Probabilities Using Normal Approximation

	WQ4WT1	WQ4WT2	WQ4WT3
WQ4WT1	1.000		
WQ4WT2	0.080	1.000	
WQ4WT3	0.005	0.013	1.000

4 Water Quality 4, Water Treatment 2 lead values were greater than Water Quality 4, Water Treatment 1 values,

1 Water Quality 4, Water Treatment 1 lead values were greater than Water Quality 4, Water Treatment 2 values,

10 Water Quality 4, Water Treatment 3 lead values were greater than Water Quality 4, Water Treatment 1 values,

0 Water Quality 4, Water Treatment 1 lead values were greater than Water Quality 4, Water Treatment 3 values,

9 Water Quality 4, Water Treatment 3 lead values were greater than Water Quality 4, Water Treatment 2 values,

1 Water Quality 4, Water Treatment 2 lead values were greater than Water Quality 4, Water Treatment 3 values.

Counts of Differences (Row Variable Greater Than Column)

	WQ1WT1	WQ1WT2	WQ1WT3
WQ1WT1	0	6	1
WQ1WT2	5	0	4
WQ1WT3	7	6	0

Z = (Sum of Signed Ranks)/Square Root (Sum of Squared Ranks)

	WQ1WT1	WQ1WT2	WQ1WT3
WQ1WT1	0		
WQ1WT2	0.357	0	
WQ1WT3	2.111	0.154	0

Two-Sided Probabilities Using Normal Approximation

	WQ1WT1	WQ1WT2	WQ1WT3
WQ1WT1	1.000		
WQ1WT2	0.721	1.000	
WQ1WT3	0.035	0.878	1.000

5 Water Quality 1, Water Treatment 2 TOC values were greater than Water Quality 1, Water Treatment 1 values,

6 Water Quality 1, Water Treatment 1 TOC values were greater than Water Quality 1, Water Treatment 2 values,

7 Water Quality 1, Water Treatment 3 TOC values were greater than Water Quality 1, Water Treatment 1 values,

1 Water Quality 1, Water Treatment 1 TOC values were greater than Water Quality 1, Water Treatment 3 values,

6 Water Quality 1, Water Treatment 3 TOC values were greater than Water Quality 1, Water Treatment 2 values,

4 Water Quality 1, Water Treatment 2 TOC values were greater than Water Quality 1, Water Treatment 3 values.

Counts of Differences (Row Variable Greater Than Column)

	WQ2WT1	WQ2WT2	WQ2WT3
WQ2WT1	0	6	4
WQ2WT2	3	0	6
WQ2WT3	5	5	0

Z = (Sum of Signed Ranks)/Square Root (Sum of Squared Ranks)

	WQ2WT1	WQ2WT2	WQ2WT3
WQ2WT1	0		
WQ2WT2	-0.302	0	
WQ2WT3	-0.178	-0.270	0

Two-Sided Probabilities Using Normal Approximation

	WQ2WT1	WQ2WT2	WQ2WT3
WQ2WT1	1.000		
WQ2WT2	0.763	1.000	
WQ2WT3	0.858	0.787	1.000

3 Water Quality 2, Water Treatment 2 TOC values were greater than Water Quality 2, Water Treatment 1 values,

6 Water Quality 2, Water Treatment 1 TOC values were greater than Water Quality 2, Water Treatment 2 values,

5 Water Quality 2, Water Treatment 3 TOC values were greater than Water Quality 2, Water Treatment 1 values,

4 Water Quality 2, Water Treatment 1 TOC values were greater than Water Quality 2, Water Treatment 3 values,

5 Water Quality 2, Water Treatment 3 TOC values were greater than Water Quality 2, Water Treatment 2 values,

6 Water Quality 2, Water Treatment 2 TOC values were greater than Water Quality 2, Water Treatment 3 values.

Counts of Differences (Row Variable Greater Than Column)

	WQ3WT1	WQ3WT2	WQ3WT3
WQ3WT1	0	6	5
WQ3WT2	5	0	5
WQ3WT3	4	5	0

Z = (Sum of Signed Ranks)/Square Root (Sum of Squared Ranks)

	WQ3WT1	WQ3WT2	WQ3WT3
WQ3WT1	0		
WQ3WT2	0.445	0	
WQ3WT3	-0.297	-0.102	0

Two-Sided Probabilities Using Normal Approximation

	WQ3WT1	WQ3WT2	WQ3WT3
WQ3WT1	1.000		
WQ3WT2	0.656	1.000	
WQ3WT3	0.766	0.919	1.000

5 Water Quality 3, Water Treatment 2 TOC values were greater than Water Quality 3, Water Treatment 1 values,

6 Water Quality 3, Water Treatment 1 TOC values were greater than Water Quality 3, Water Treatment 2 values,

4 Water Quality 3, Water Treatment 3 TOC values were greater than Water Quality 3, Water Treatment 1 values,

5 Water Quality 3, Water Treatment 1 TOC values were greater than Water Quality 3, Water Treatment 3 values,

5 Water Quality 3, Water Treatment 3 TOC values were greater than Water Quality 3, Water Treatment 2 values,

5 Water Quality 3, Water Treatment 2 TOC values were greater than Water Quality 3, Water Treatment 3 values.

Counts of Differences (Row Variable Greater Than Column)

	WQ4WT1	WQ4WT2	WQ4WT3
WQ4WT1	0	7	5
WQ4WT2	3	0	3
WQ4WT3	5	5	0

Z = (Sum of Signed Ranks)/Square Root (Sum of Squared Ranks)

	WQ4WT1	WQ4WT2	WQ4WT3
WQ4WT1	0		
WQ4WT2	-1.746	0	
WQ4WT3	-0.819	1.292	0

Two-Sided Probabilities Using Normal Approximation

	WQ4WT1	WQ4WT2	WQ4WT3
WQ4WT1	1.000		
WQ4WT2	0.081	1.000	
WQ4WT3	0.413	0.196	1.000

3 Water Quality 4, Water Treatment 2 TOC values were greater than Water Quality 4, Water Treatment 1 values,

7 Water Quality 4, Water Treatment 1 TOC values were greater than Water Quality 4, Water Treatment 2 values,

5 Water Quality 4, Water Treatment 3 TOC values were greater than Water Quality 4, Water Treatment 1 values,

5 Water Quality 4, Water Treatment 1 TOC values were greater than Water Quality 4, Water Treatment 3 values,

5 Water Quality 4, Water Treatment 3 TOC values were greater than Water Quality 4, Water Treatment 2 values,

3 Water Quality 4, Water Treatment 2 TOC values were greater than Water Quality 4, Water Treatment 3 values.

Appendix B: Photographs of Copper Pipe Test Specimens

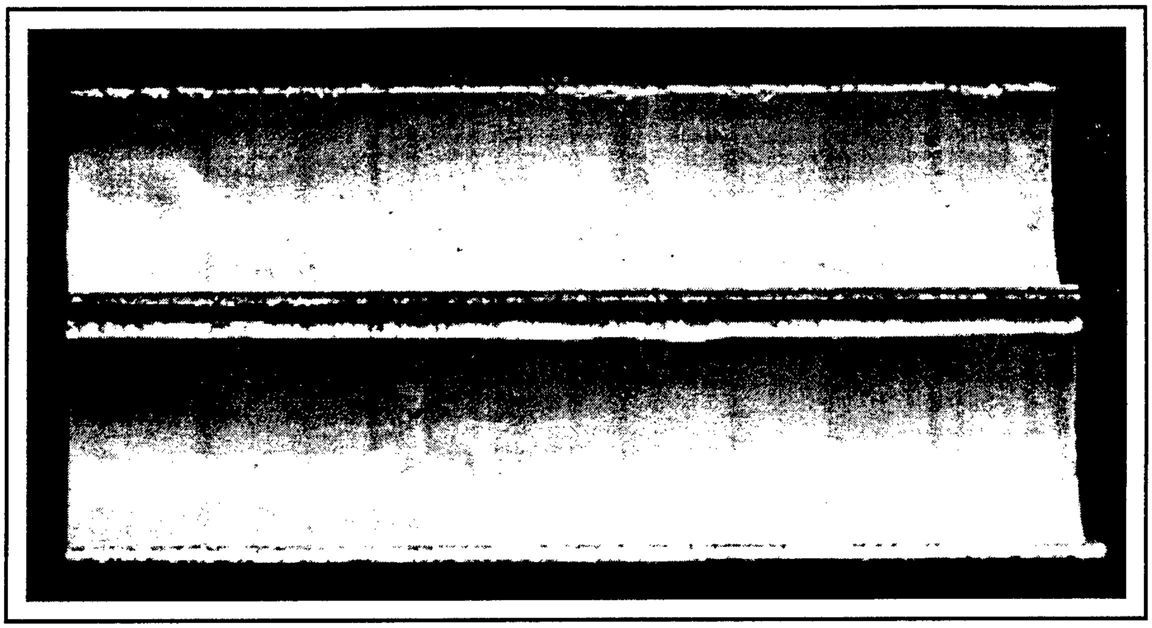

Figure B1. Specimen C11 (in-situ epoxy coating, hard water, 5 fps).

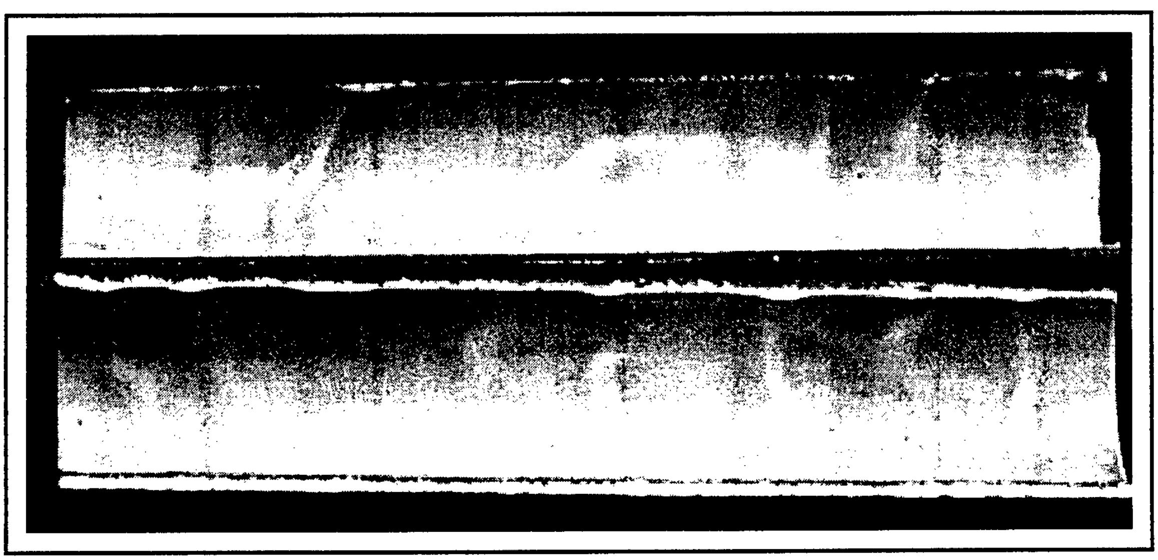

Figure B2. Specimen P11 (in-situ epoxy coating, hard water, 5 fps).

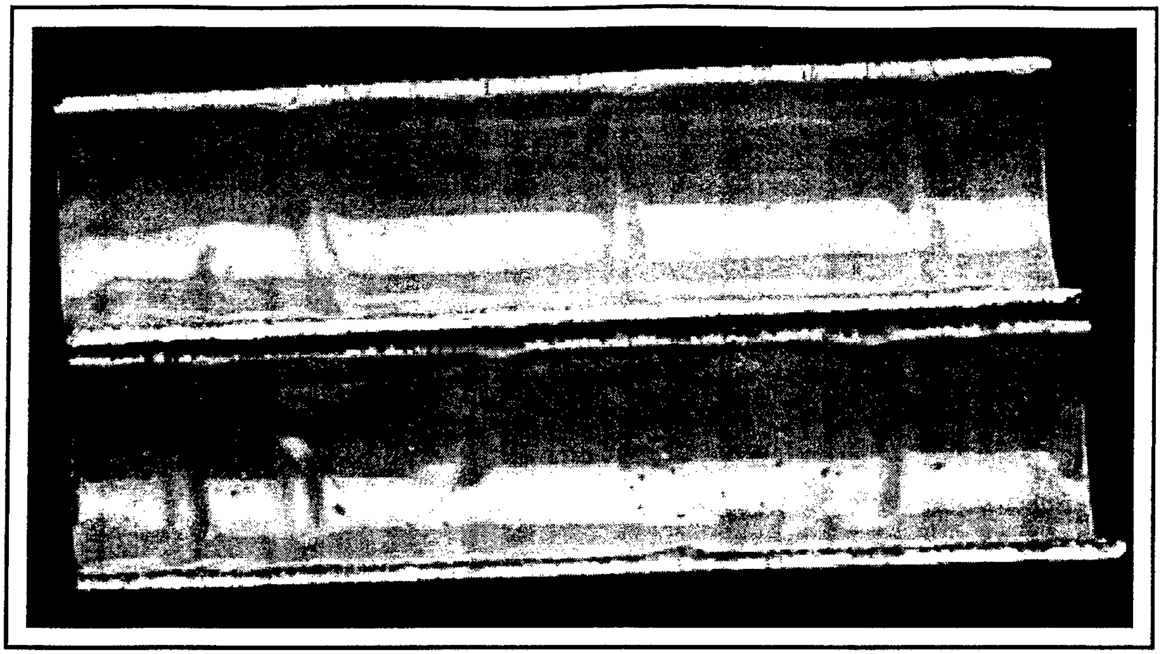

Figure B3. Specimen C14 (in-situ epoxy coating, soft water, 5 fps).

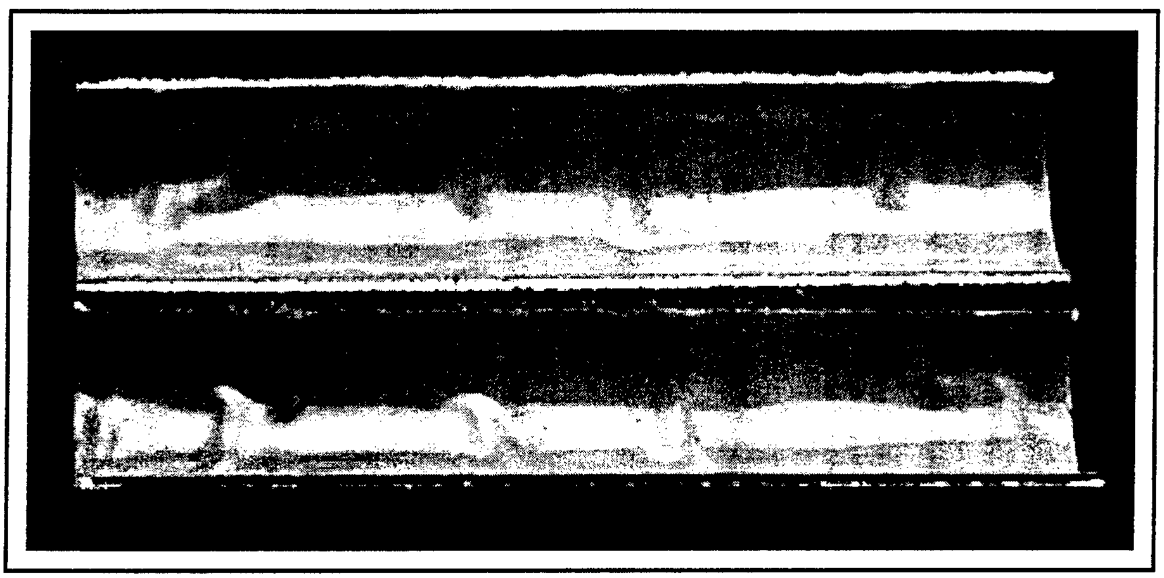

Figure B4. Specimen P14 (in-situ epoxy coating, soft water, 5 fps).

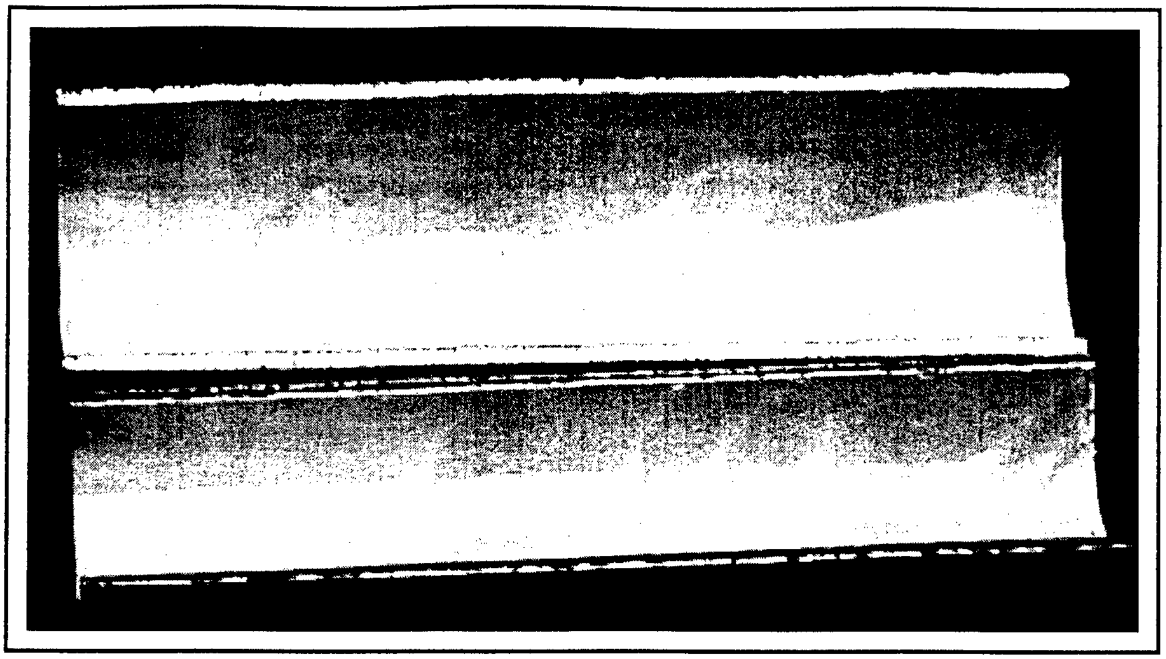

Figure B5. Specimen C10 (in-situ epoxy coating, hard water, 3 fps).

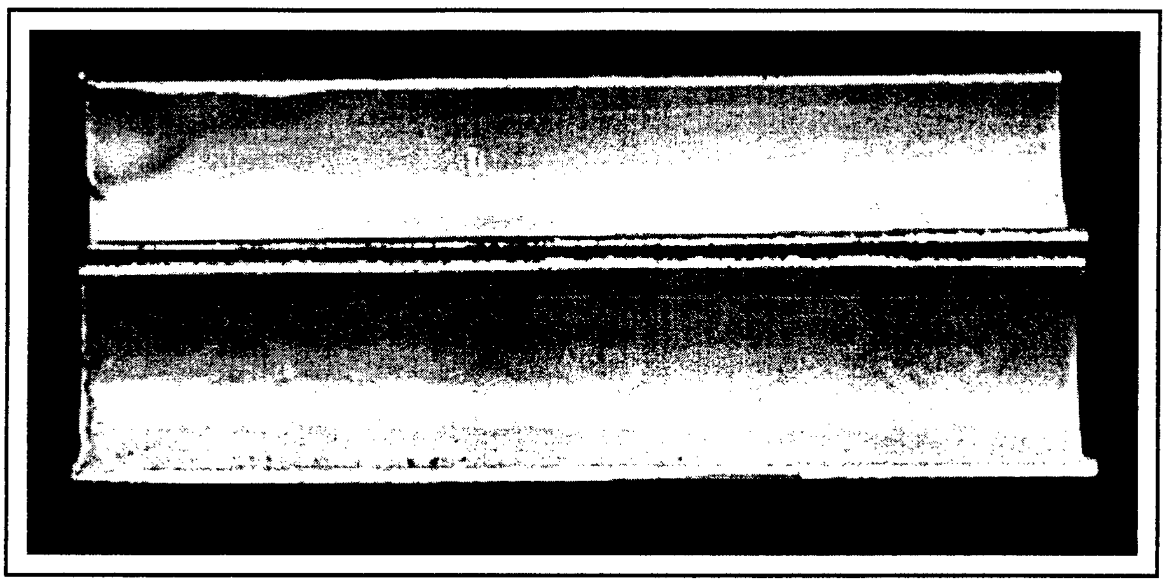

Figure B6. Specimen P10 (in-situ epoxy coating, hard water, 3 fps).

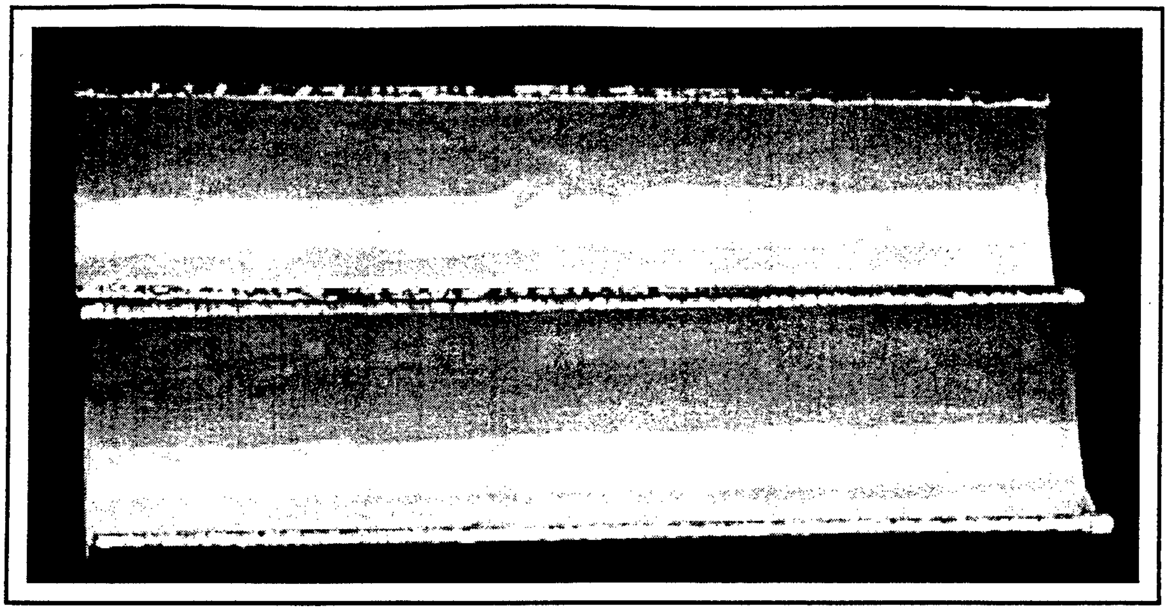

Figure B7. Specimen C12 (in-situ epoxy coating, soft water, 3 fps).

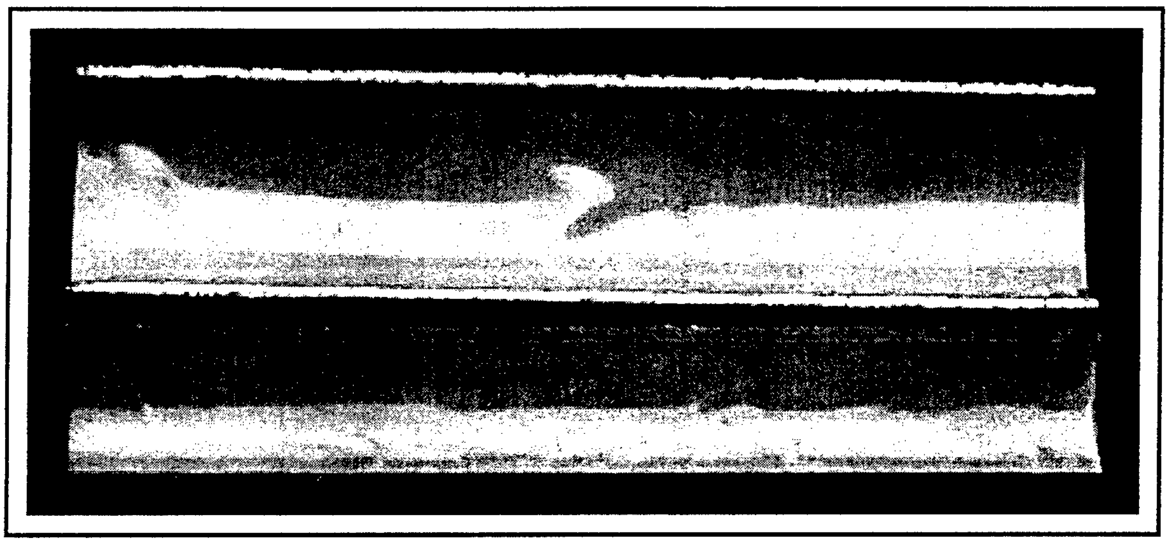

Figure B8. Specimen P12 (in-situ epoxy coating, soft water, 3 fps).

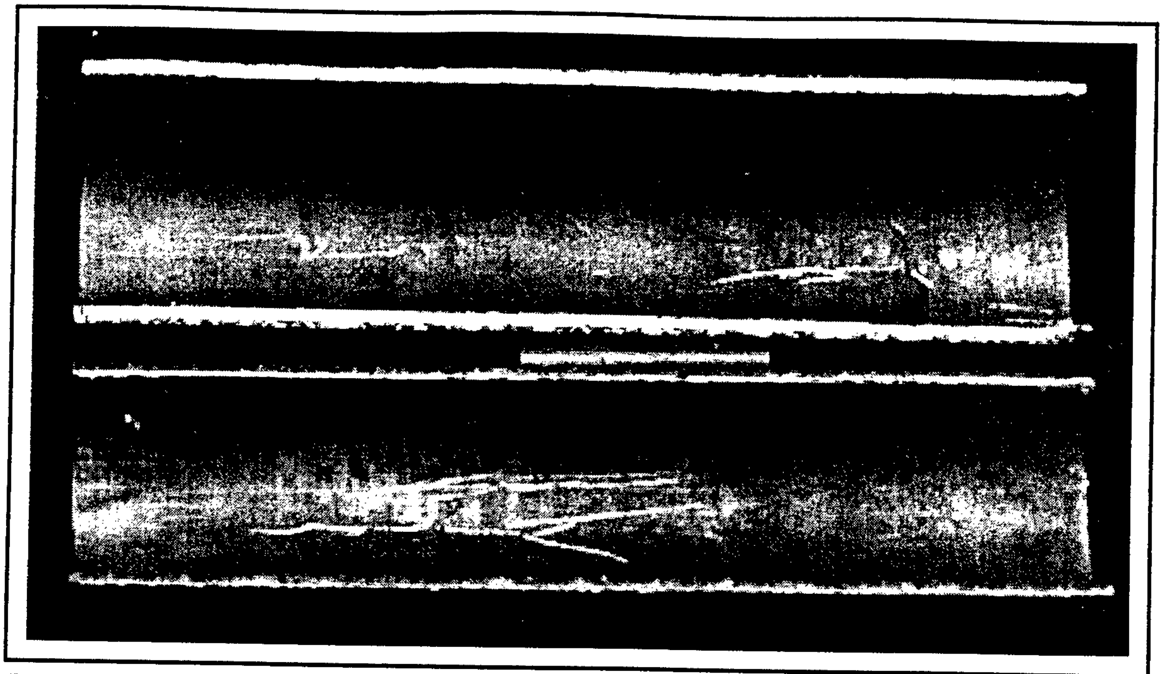

Figure B9. Specimen C06 (zinc orthophosphate, hard water, 5 fps).

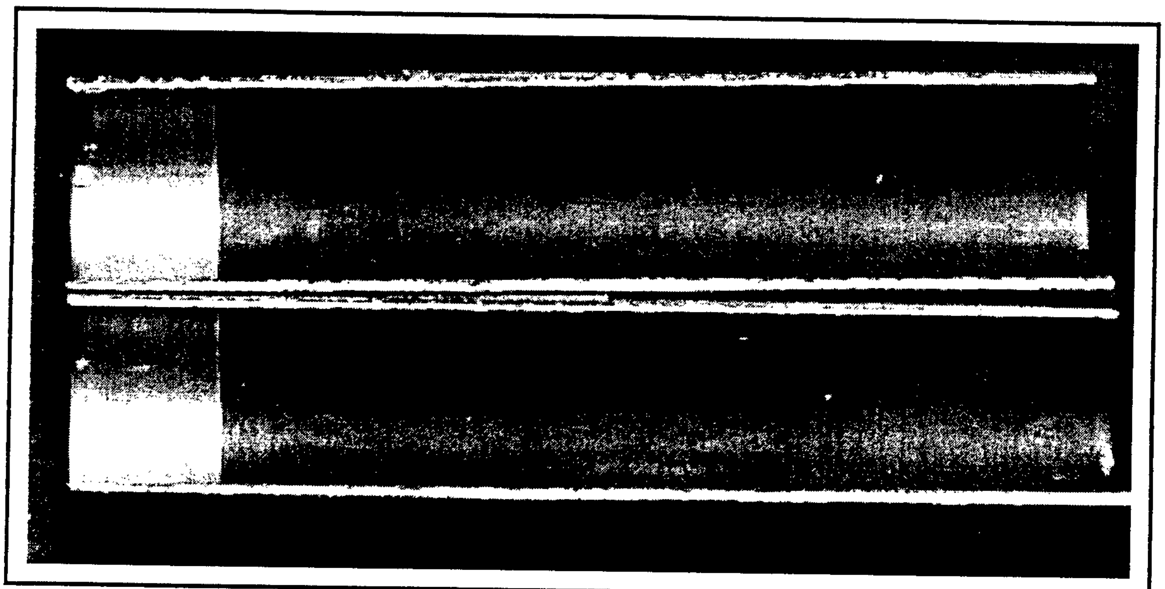

Figure B10. Specimen P06 (zinc orthophosphate, hard water, 5 fps).

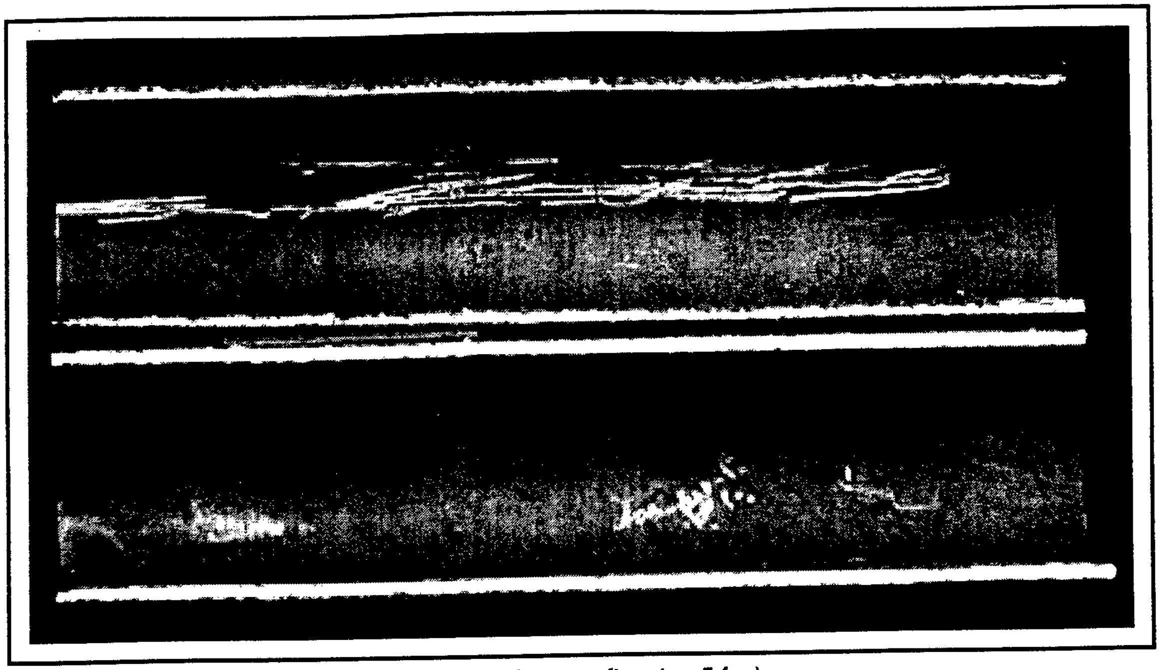

Figure B11. Specimen C09 (zinc orthophosphate, soft water, 5 fps).

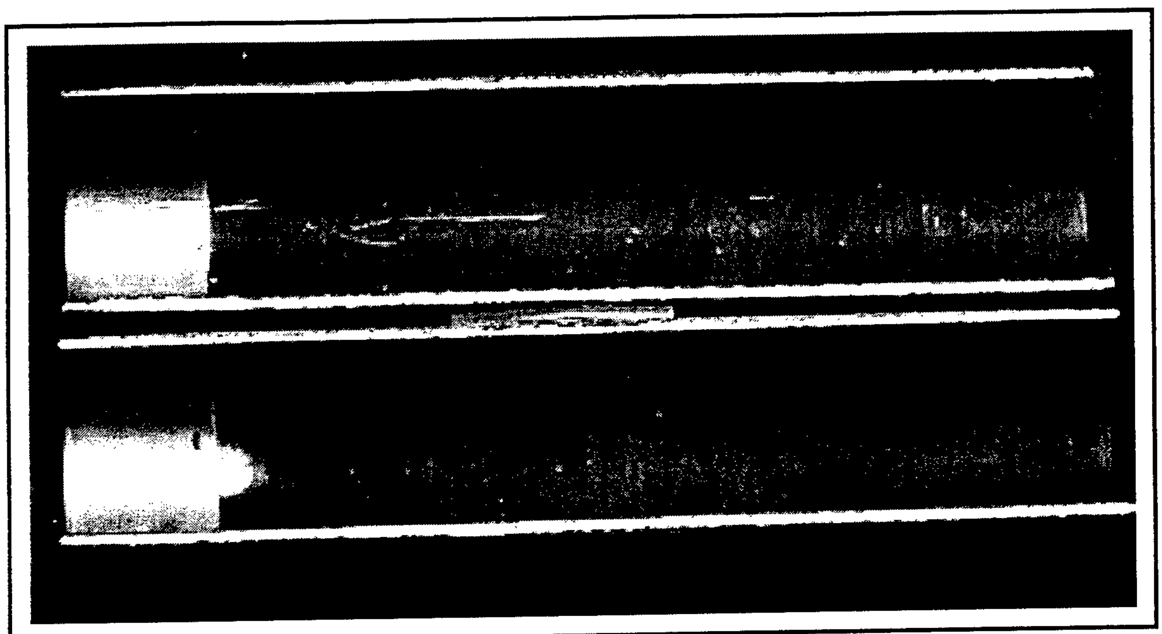

Figure B12. Specimen P09 (zinc orthophosphate, soft water, 5 fps).

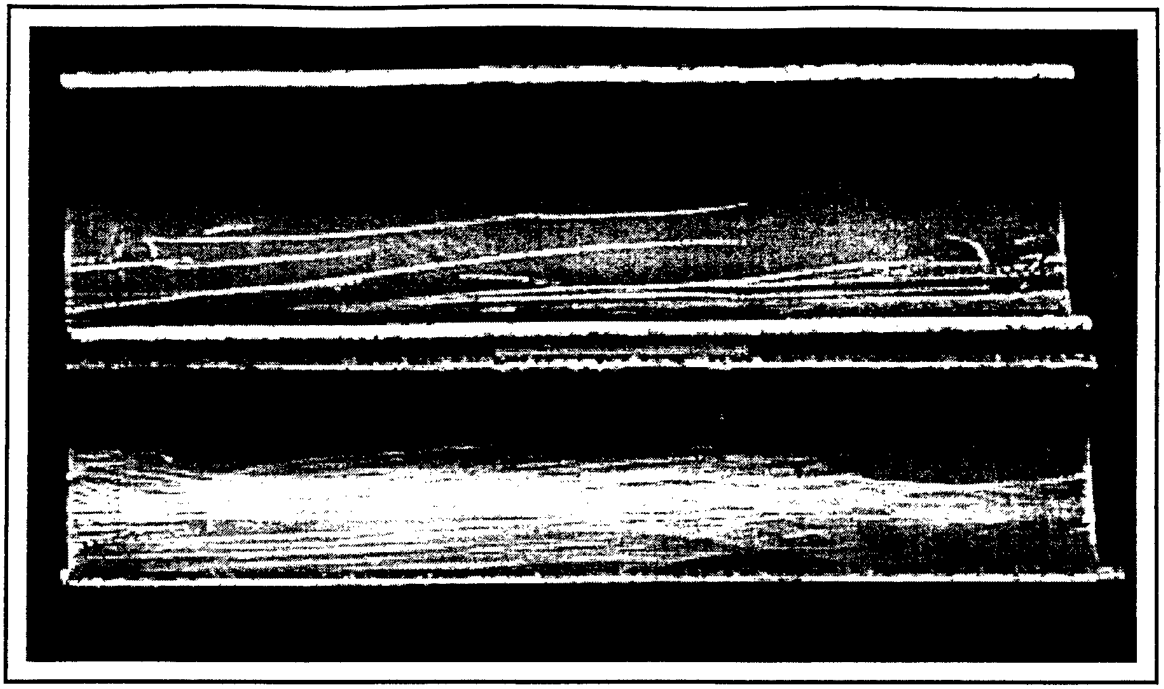

Figure B13. Specimen C07 (zinc orthophosphate, hard water, 3 fps).

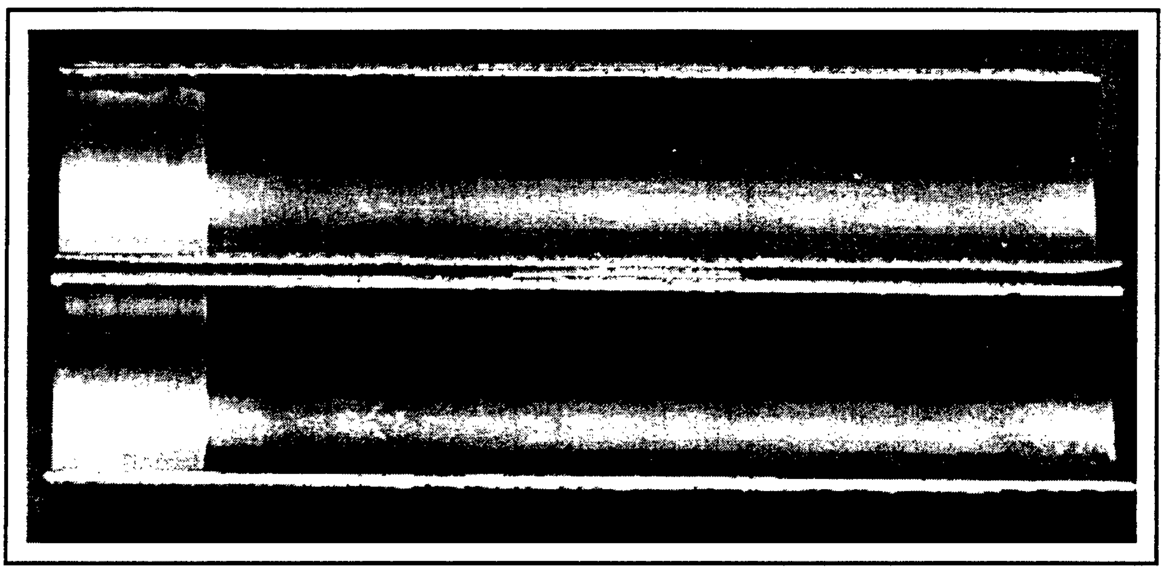

Figure B14. Specimen P07 (zinc orthophosphate, hard water, 3 fps).

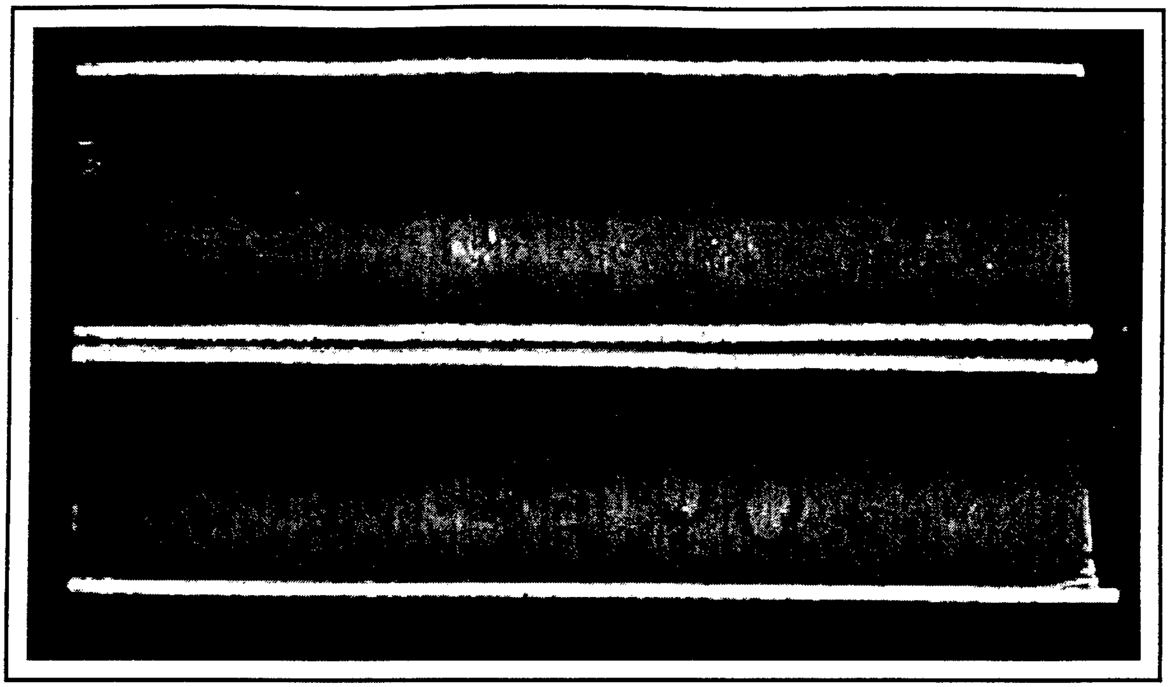

Figure B15. Specimen C08 (zinc orthophosphate, soft water, 3 fps).

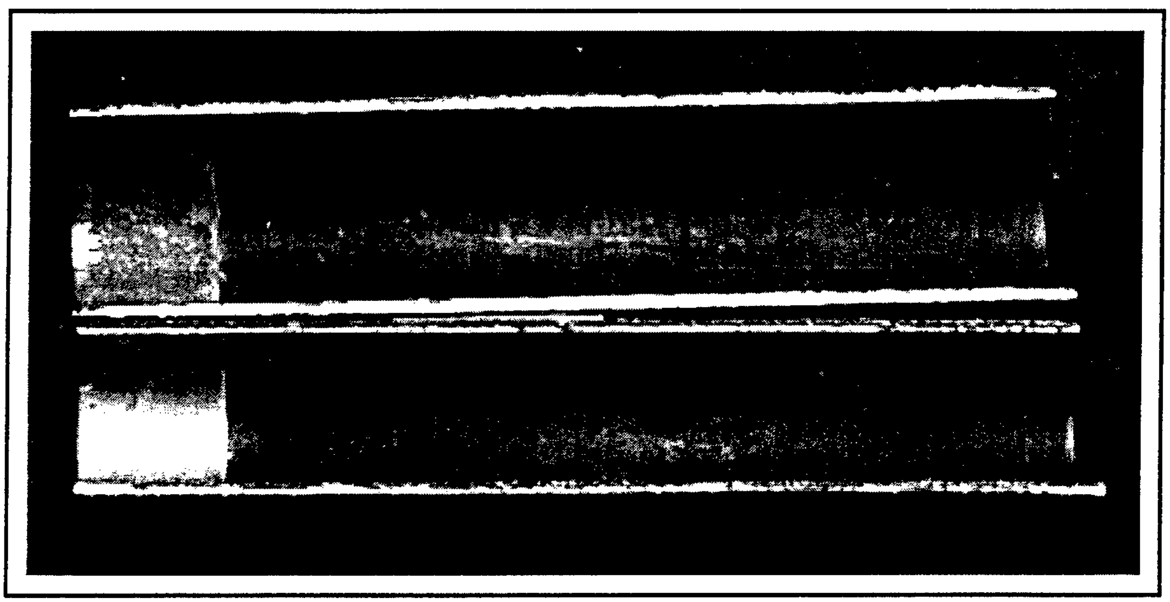

Figure B16. Specimen P08 (zinc orthophosphate, soft water, 3 fps).

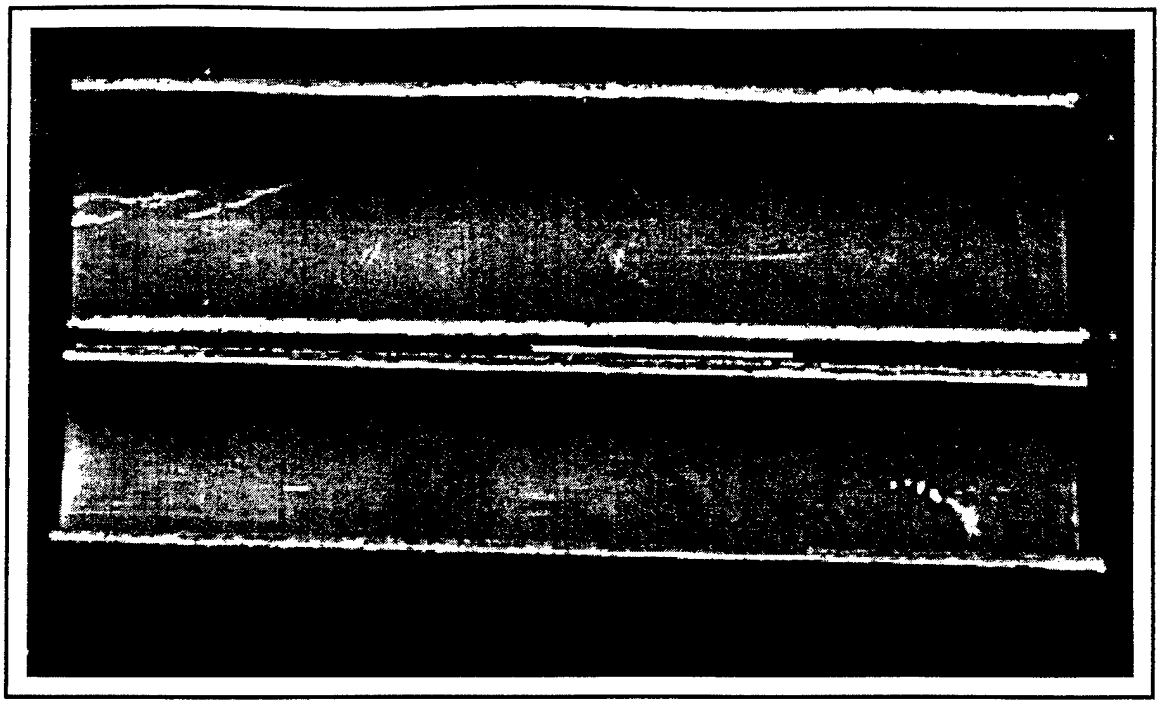

Figure B17. Specimen C13 (control, hard water, 5 fps).

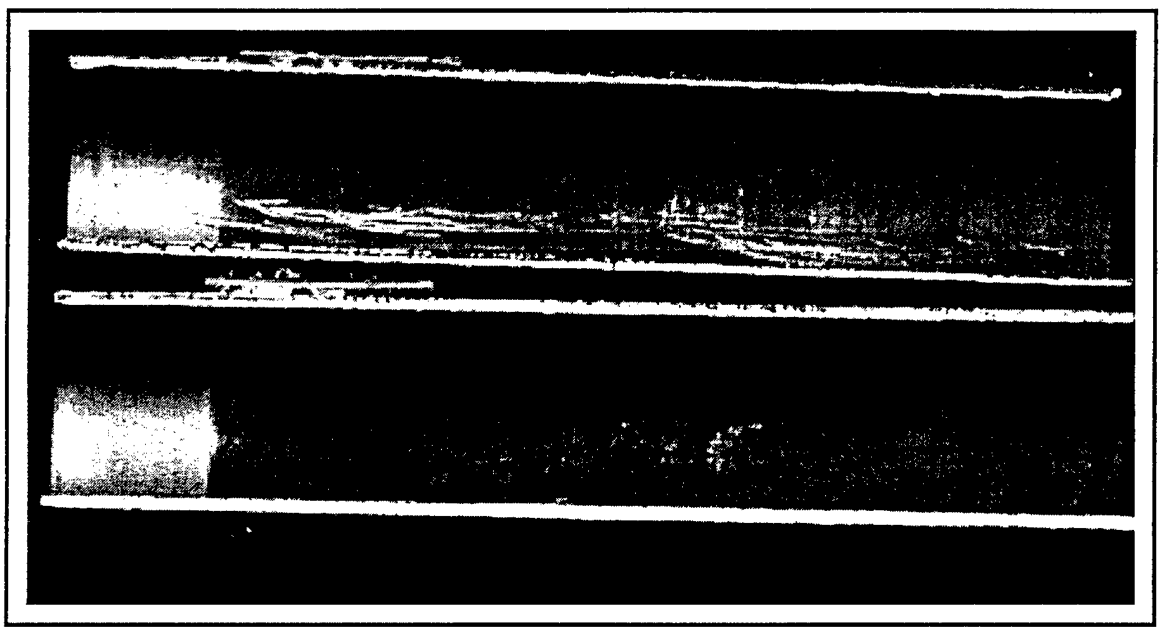

Figure B18. Specimen P13 (control, hard water, 5 fps).

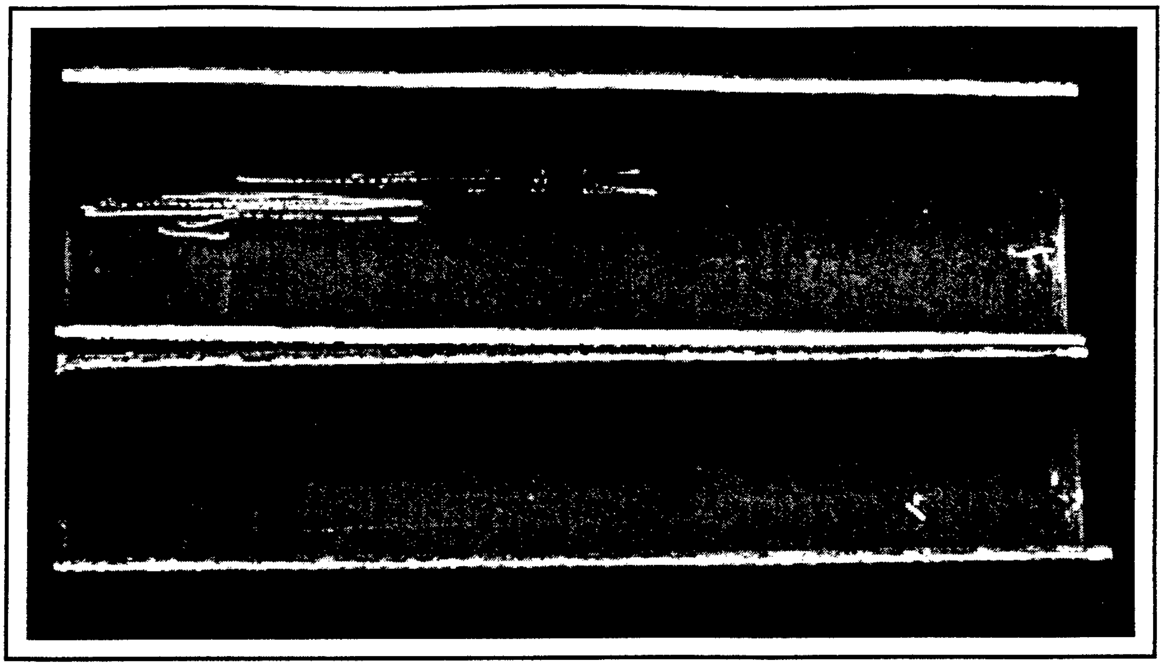

Figure B19. Specimen C01 (control, soft water, 5 fps).

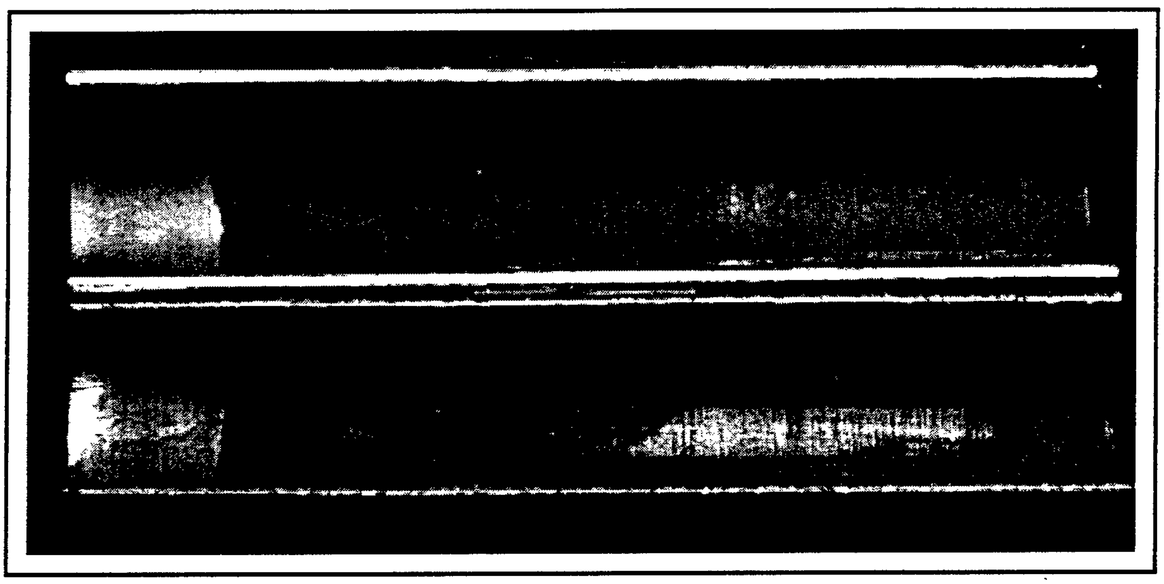

Figure B20. Specimen P01 (control, soft water, 5 fps).

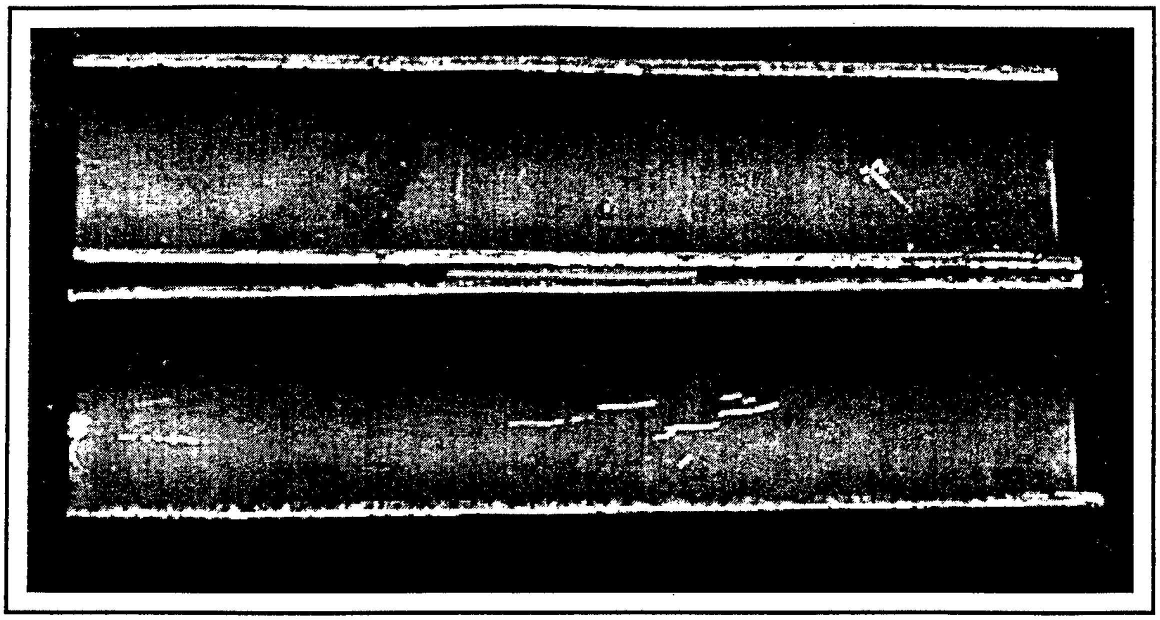

Figure B21. Specimen C02 (control, hard water, 3 fps).

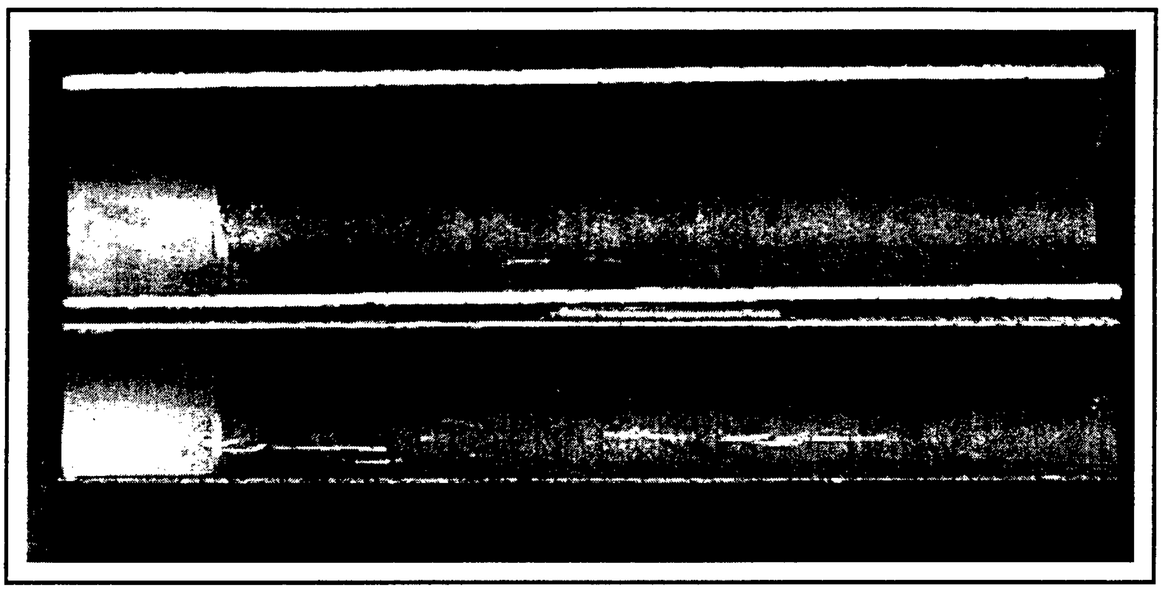

Figure B22. Specimen P02 (control, hard water, 3 fps).

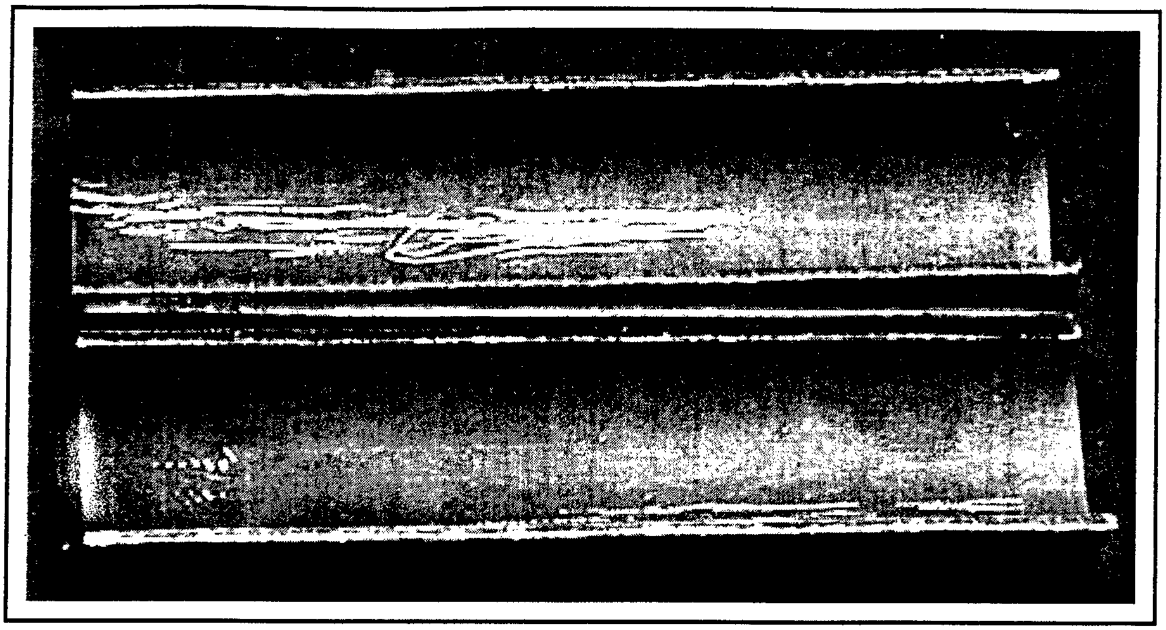

Figure B23. Specimen C03 (control, soft water, 3 fps).

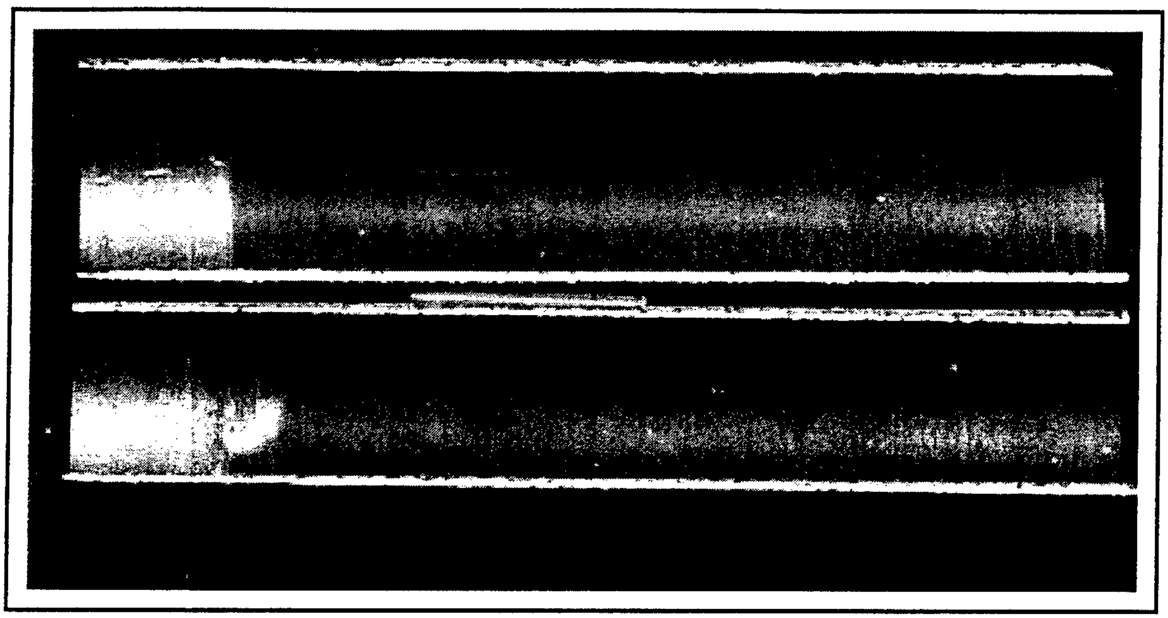

Figure B24. Specimen P03 (control, soft water, 3 fps).

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14. ABSTRACT

Corrosion of building plumbing can result in reduced service life and adverse health effects such as those associated with high lead blood levels, particularly in children. The U.S. Environmental Protection Agency (USEPA) has established an "Action Level" (AL) of 15 μg/L for lead and 1.3 mg/L for copper in drinking water. Army installations must comply with the increasingly stringent drinking water quality standards enacted at the Federal level and enforced by State regulations.

This study evaluated the effectiveness of in-situ coatings for inhibiting lead corrosion under a variety of water quality parameters in the laboratory. The study compared the in-situ coating system to zinc orthophosphate chemical inhibitor treatment for mitigation corrosion and plumbosolvency. Results indicate that the in-situ epoxy coating provides an effective alternative to conventional chemical treatment for the prevention of lead and copper metal release in a system modeled to simulate a home plumbing system. This study also initiated operation of a Water Treatment Test Facility (WTTF) to determine its viability as a test facility to simulate a variety of water qualities in a home plumbing system. The WTTF operated reliably over the course of the 12-week study, and produced valuable information on operating procedures.

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